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## Water Quality Sampling at Pictured Rocks and Sleeping Bear Dunes National Lakeshores, 2005

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## Introduction

The Great Lakes Inventory and Monitoring Network (hereafter the Network or GLKN) measured water quality variables and collected water samples in Pictured Rocks National Lakeshore (PIRO) and Sleeping Bear Dunes National Lakeshore (SLBE) in 2005. The purpose of this work was twofold. First, in order to use diatoms as a biomonitoring indicator, current diatom communities must be calibrated with current water quality conditions. Multiple chemical and physical samples need to be collected over the course of the season to characterize mean lake conditions. As part of the Network's agreement with St. Croix Watershed Research Station (SCWRS) on the diatom project, as it is commonly known (project # R210504028), the Network agreed to collect water quality data during the open water season and surface sediment samples at the end of the season. The St. Croix Watershed Research Station agreed to collect long cores from a subset of lakes to determine historical water quality conditions, and surface sediment samples for analysis of diatom communities relative to current water quality conditions.

The second reason this water quality sampling project was undertaken was to test the sampling design and methods proposed in a draft protocol for monitoring water quality of inland lakes in Great Lakes Network parks. Water quality as a vital sign ranked high across Network parks and monitoring water quality is mandated by the National Park Service Water Resources Division. The sooner we could begin to test our proposed sampling design and understand logistical challenges, the more prepared we would be for eventual long-term monitoring.

This report summarizes the Network's activities related to the diatom project in 2005. A separate report, detailing progress on diatom analyses, will be written by the principal investigators (Drs. Dan Engstrom and Mark Edlund, SCWRS, and Dr. Brenda Lafrancois, NPS). Data from 2005 will be compared with data collected in previous years only after the details of field and laboratory methods for past work are known and deemed comparable.

## Water Quality Sampling

### Field Methods

We conducted field sampling at the deepest part of each lake (Table 1) four times throughout the open water season (Table 2). Because both PIRO and SLBE had previous water quality sampling projects, staff knew where the appropriate sampling location was in each lake. I relied heavily on Lora Loope at PIRO and Paul Murphy and Tom Van Zoeren at SLBE for assistance in all aspects of the 2005 project.

Profile data on temperature, dissolved oxygen concentration, specific conductance, and pH were collected near the surface and at 1 m intervals to the bottom. At each site, we also measured Secchi depth, took a GPS reading, recorded environmental conditions (e.g., wind speed and direction, wave height, sky cover, air temperature), and noted field personnel and instruments.

The parks' own multi-probe sondes were used to collect the profile data. At Pictured Rocks this was a Yellow Springs Instrument (YSI); at SLBE, a HydroLab. Midway through the season, SLBE acquired a new HydroLab. We compared the new and old sondes and found small differences that were within the acceptable ranges (Irwin 2004). The sondes were calibrated daily for dissolved oxygen and pH, and once, prior to the season, for specific conductance.

We collected 0-2 m integrated water samples for laboratory analyses using an integrated tube sampler (MPCA 2004a, b; WDNR 2004). On lakes that were less than 2 m deep, we used the tube sampler on an angle to collect a sample from the full water column. Two tubes-full of water were composited in a 4.3 L high density polyethylene container. A 1 L brown polyethylene bottle was filled from the composite container, and the composite container was topped off with additional water from the integrated sampling tube. Both bottles were stored in a cooler on ice until further processing could be completed.

At the beginning of the season we conducted equipment blanks to ensure we were not introducing any contamination to the samples. During each round of sampling, we collected replicate samples from one randomly selected lake at each park. We fabricated a station code and date and time of collection for each sample to disguise its status as a duplicate sample. Every site had an alpha-numeric identification code.

Table 1. Lakes sampled for water quality in 2005. PIRO = Pictured Rocks National Lakeshore; SLBE = Sleeping Bear Dunes National Lakeshore.

<b>Park Code</b>	<b>Lake Name</b>	<b>Lake Maximum Depth (m)</b>	<b>Lake Surface Area (ha)</b>
PIRO	Grand Sable	19	255
PIRO	Trappers	<2	18
PIRO	Chapel	42	28
PIRO	Beaver	10	310
PIRO	Little Beaver	5	16
PIRO	Miners	4	5
SLBE	Manitou	14	104
SLBE	Florence	8	32
SLBE	Shell	4	41
SLBE	Bass (Leelenau)	9	38
SLBE	School	<2	71
SLBE	Tucker	3	7
SLBE	North Bar	10	12
SLBE	Loon	19	37
SLBE	Round	8	6

Table 2. Dates of water quality sampling in 2005. PIRO = Pictured Rocks National Lakeshore; SLBE = Sleeping Bear Dunes National Lakeshore.

<b>Park Code</b>				
PIRO	May 16 - May 19	June 27 - June 29	Aug. 1 – Aug. 3	Sept. 12 - Sept. 15
SLBE	May 23 - May 26	June 27 - July 5	Aug. 8 – Aug. 11	Sept. 26 - Sept. 30

### **Analytical Laboratory**

We contracted with White Water Associates (WWA) for analytical laboratory services. After receiving the results from the first sampling, we decided to send duplicate samples to SCWRS (Table 3) for comparison due to the large number of samples that were below WWA's method detection limits. Methods for sample processing differed slightly between the laboratories, as described below.

### **Sample Processing**

Most samples were processed in the park's laboratory space at the end of each sampling day. However, at remote sites, sample water was processed in the field in order to halt biological activity and preserve the samples in a timely manner.

### ***Processing for White Water Associates Laboratory***

Water from the 1 L brown bottle was filtered through a Whatman GF/C paper filter for analysis of chlorophyll-*a* (chl-*a*). The volume of water passed through the filter was recorded (1000 ml or until the filter began to clog, whichever came first). The filter was then folded into quarters, wrapped in aluminum foil, placed in a small plastic bag, and frozen for later analysis.

Water from the composite container was processed in various ways, depending on the analyte to be measured. One bottle was filled with raw sample water and preserved with H<sub>2</sub>SO<sub>4</sub> for analyses of total phosphorus (TP), total Kjeldahl nitrogen (TKN), ammonia (NH<sub>4</sub>-N), and nitrate/nitrite-nitrogen (NO<sub>3</sub>/NO<sub>2</sub>-N). A second bottle was filled with raw sample water, without a preservative, for analysis of alkalinity (alk), chloride (Cl<sup>-</sup>), and sulfate (SO<sub>4</sub><sup>-2</sup>). Water from the remaining composite sample was filtered through a Millipore 0.45 µm membrane filter, then split into three bottles: 1) preserved with H<sub>2</sub>SO<sub>4</sub> for analysis of dissolved organic carbon (DOC), 2) preserved with HNO<sub>3</sub> for analysis of cations (calcium (Ca<sup>+</sup>), sodium (Na<sup>+2</sup>), magnesium (Mg<sup>+2</sup>), and potassium (K<sup>+</sup>)), and 3) without a preservative for analysis of dissolved silicon dioxide (SiO<sub>2</sub>; the first round of samples was not filtered; subsequent samples were filtered). All bottles were then stored in the refrigerator until shipped to the laboratory. A bottle of tap water was refrigerated, stored, and shipped with the samples to serve as a temperature check.

### ***Processing for St. Croix Watershed Research Station Laboratory***

Cations and chlorophyll-*a* were not analyzed by SCWRS. Raw sample water from the composite container was used to fill one bottle for analysis of TP and TN. This sample was kept frozen until analysis at the laboratory. Water was filtered through a Millipore 0.45 µm membrane filter, then split into two bottles: 1) without preservative for analyses of SiO<sub>2</sub>, SO<sub>4</sub><sup>-2</sup>, and Cl<sup>-</sup>, and 2) preserved with H<sub>2</sub>SO<sub>4</sub> for analyses of DOC and NO<sub>3</sub>/NO<sub>2</sub>-N. Bottles of filtered sample water were refrigerated until shipping to the laboratory. A bottle of tap water was stored and shipped with the samples to serve as a temperature check.

Water quality variables analyzed by each laboratory are indicated in Table 3.

## Shipping Samples to the Laboratory

Sampling at PIRO was usually completed between Monday and Thursday, and samples were sent Thursday afternoon via overnight FedEx to the laboratories or delivered personally by the Network's aquatic ecologist. Sampling at SLBE was completed from Monday through Friday, and samples were either sent the following Monday via overnight FedEx or delivered personally by the Network's aquatic ecologist on Saturday. Refrigerated samples were packed in a cooler surrounded by bags and bottles of ice, along with a temperature check bottle. Frozen filters for chlorophyll-*a* analysis were bundled together in double plastic bags and sandwiched between bags of ice. Frozen nutrient samples were packed on ice in a small cooler within a larger cooler with the remaining samples. All samples arrived at the respective laboratories within recommended holding times in good condition and at acceptable temperatures.

Table 3. Water quality variables analyzed by lab and by sampling period. WWA = White Water Associates, SCWRS = St. Croix Watershed Research Station, analyte abbreviations as in text.

	Chl- <i>a</i>	TP/TN	NO <sub>3</sub> /NO <sub>2</sub> - N	NH <sub>4</sub> -N	DOC	Alkalinity	Cl, SO <sub>4</sub>	Ca, Na, K, Mg	SiO <sub>2</sub>
May	WWA	WWA	WWA	WWA	WWA	WWA	WWA	WWA	WWA
June	WWA	WWA	WWA		WWA	WWA	WWA		WWA
		SCWRS	SCWRS		SCWRS		SCWRS		
Aug	WWA	SCWRS	SCWRS		SCWRS	WWA	SCWRS	WWA	SCWRS
Sept	WWA	SCWRS	SCWRS		WWA	WWA	WWA		WWA
					SCWRS		SCWRS		SCWRS

## Sediment Sampling

Surface sediment samples were collected with a drop corer at approximately the same locations as the measurements of physical and chemical variables. The top 1 cm of sediment (0-1 cm) was collected for each lake, and a 1-2 cm sample was also collected from lakes with flocculent surface sediments. At SLBE, the samples were collected during the final water quality sampling period, September 26-30. The Loon Lake sample was not collected properly, so another sample was collected in spring, 2006, prior to stratification. At PIRO, a sample from Trappers Lake was collected during the final sampling in September; samples from remaining lakes were collected in October.

Samples were placed in plastic containers, kept cold and dark in the field, and stored in the refrigerator until transport to SCWRS.

The principal investigators collected long cores from Grand Sable Lake (PIRO), Lake Manitou (SLBE), Bass Lake (Leelenau; SLBE), and Shell Lake (SLBE). Approximately 1 - 2 m of sediment was collected from each lake, and sliced into 1 cm sections. Each slice was placed in a plastic container, kept cold and dark in the field, and stored in the refrigerator until transport to SCWRS.

## Results and Discussion

### Pictured Rocks National Lakeshore

The lakes in PIRO were aesthetically pleasing and water quality appeared good, however, total nitrogen (TN) and total phosphorus (TP) values exceeded EPA criteria for Ecoregion VIII in several lakes on multiple occasions (Table 4, and see Appendix A for all data.) Criteria for the subecoregion containing PIRO (Level III ecoregion 50) are 0.40 mg/L for TN and 9.69 µg/L for TP (USEPA 2000a). Trappers Lake was the only lake to exceed the TN criterion, which it did consistently throughout the season. Beaver, Little Beaver, Trappers, and Miners Lakes exceeded the TP criterion during every sampling period, while Grand Sable Lake exceeded the criterion twice and Chapel Lake, once (note that laboratory data from White Water Associates were not used, as the lab's method detection limits were too high). Chlorophyll-*a* and Secchi depth, which are considered response variables, also did not meet the USEPA criteria of 2.46 µg/L and 4.2 m, respectively, in all lakes on multiple occasions.

Concentrations of dissolved silica, a nutrient required by diatoms and some chrysophyte algae (Wetzel 2001), were generally lowest early in the season (Appendix A). The concentration remained virtually the same throughout the season in Grand Sable Lake, but at least doubled in Trappers Lake between June and September. The May data were not included in this interpretation because the samples were raw instead of filtered, but if they were included, the concentration in Trappers Lake may have risen by as much as 60x. Interpretation of silica data is confounded by inconsistent results between laboratories, especially at low levels. Likely the concentration of dissolved silica was adequate throughout the season and did not affect algal community composition.

The TN:TP ratios indicate all PIRO lakes are phosphorus limited (Table 5), if 10 (Scheffer 2004) or 7 (Dillon et al. 2004) is used as the critical value (by weight). If we use ratios greater than 15 (Shaw et al. 1996) to indicate phosphorus limitation, then Beaver and Little Beaver Lakes may be considered to be transitional. Production of algae in lakes is more commonly limited by phosphorus than nitrogen (Wetzel 2001). Lower TN:TP ratios provide conditions that favor cyanobacteria, as this group can fix nitrogen. Cyanobacteria are usually not common at TN:TP ratios greater than 29 (Wetzel 2001) and often dominate at ratios lower than 5 to 10 (Bulgakov and Levich, accessed 6/30/06).

Specific conductance values of lakes at PIRO were relatively high, indicative of hardwater lakes (<http://waterontheweb.org/under/lakeecology/07%5Fchemical.html>). Concentrations of cations ( $\text{Ca}^+$ ,  $\text{Na}^{+2}$ ,  $\text{K}^+$ ,  $\text{Mg}^{+2}$ ) and anions ( $\text{Cl}^-$ ,  $\text{SO}_4^{-2}$ ) are derived primarily through weathering of the surrounding rocks and soils. The ionic strength of PIRO lakes is typical of unpolluted fresh waters in the Upper Peninsula of Michigan, with most parameters measuring within the ranges reported in the Environmental Protection Agency's (EPA's) water quality database (STORET; [http://www.epa.gov/storet/dw\\_home.html](http://www.epa.gov/storet/dw_home.html)). Calcium concentrations in most lakes are high enough (>20 mg/L) to support the exotic zebra mussel (*Dreissena polymorpha*) (Cohen 2004). Most of the sampled lakes are drainage lakes and receive water through flowing surface water, and likely through groundwater discharge. Trappers Lake is the only seepage lake, but likely has a connection to the groundwater table as its ionic strength is similar to the other lakes.

Table 4. Average values of field and laboratory variables measured at Pictured Rocks National Lakeshore, 2005. N = number of samples. Laboratory analyses conducted by White Water Associates and St. Croix Watershed Research Station (*italics*). When analytes were below method detection limits (DL), ½ DL was used in calculations. Field measurements included Secchi depth, pH, and specific conductance (EC25). Near-surface values were used for pH and specific conductance.

Variable	N	Grand Sable	Trappers	Chapel	Beaver	Little Beaver	Miners
Chl- <i>a</i> (µg/L)	4	3.33	3.29	2.90	5.10	9.40	1.99
TP (mg/L)	2	0.04	0.04	0.02	0.04	0.05	0.02
	<i>2 or</i>						
TP (µg/L)	3	<i>8.11</i>	<i>10.00</i>	<i>8.58</i>	<i>12.22</i>	<i>21.20</i>	<i>16.34</i>
TKN (mg/L)	2	0.36	0.75	0.36	0.20	0.42	0.43
	<i>2 or</i>						
TN (mg/L)	3	<i>0.21</i>	<i>0.74</i>	<i>0.23</i>	<i>0.18</i>	<i>0.31</i>	<i>0.42</i>
NO <sub>3</sub> /NO <sub>2</sub> - N (mg/L)	2	0.03	0.01	0.01	0.01	0.20	0.22
	<i>2 or</i>						
NO <sub>3</sub> /NO <sub>2</sub> - N (mg/L)	3	<i>0.008</i>	<i>0.010</i>	<i>0.016</i>	<i>0.006</i>	<i>0.005</i>	<i>0.097</i>
NH <sub>4</sub> -N (mg/L)	1	0.06	0.11	0.09	0.07	0.07	0.13
DOC (mg/L)	3	6.5	8.9	8.4	4.7	6.8	7.4
	<i>2 or</i>						
DOC (mg/L)	3	<i>5.6</i>	<i>9.7</i>	<i>7.3</i>	<i>3.6</i>	<i>5.5</i>	<i>5.6</i>
Alkalinity (mg/L)	4	46	70	86	76	66	142
Cl (mg/L)	3	0.5	0.4	0.5	0.5	0.5	1.4
	<i>2 or</i>						
Cl (mg/L)	3	<i>0.30</i>	<i>0.28</i>	<i>0.28</i>	<i>0.37</i>	<i>0.29</i>	<i>1.24</i>
SO <sub>4</sub> (mg/L)	3	4.3	3.2	7.9	4.3	5.2	6.4
	<i>2 or</i>						
SO <sub>4</sub> (mg/L)	3	<i>4.47</i>	<i>4.45</i>	<i>8.31</i>	<i>6.65</i>	<i>7.52</i>	<i>8.41</i>
Ca (mg/L)	2	14.09	23.26	21.91	26.00	20.69	32.77
Na (mg/L)	2	0.93	1.06	0.80	1.09	1.03	1.30
K (mg/L)	2	0.75	0.59	0.68	0.62	0.63	0.63
Mg (mg/L)	2	5.09	5.52	10.49	5.46	5.74	16.83
SiO <sub>2</sub> (mg/L)	2	4.4	4.2	4.4	8.5	6.9	6.5
SiO <sub>2</sub> (mg/L)	2	<i>4.75</i>	<i>5.88</i>	<i>4.41</i>	<i>9.29</i>	<i>6.52</i>	<i>6.60</i>
Secchi depth (m)	4	3.9	bottom	3.6	3.9	2.8	2.5
pH (std. units)	4	8.0	8.5	8.1	8.2	8.2	7.8
EC25 (µS/cm)	4	110	148	187	164	165	278

Table 5. Total nitrogen to total phosphorus (TN:TP) ratios for lakes in Pictured Rocks National Lakeshore, 2005, using data from St. Croix Watershed Research Station. NA = not available

	Grand Sable	Trappers	Chapel	Beaver	Little Beaver	Miners
Jun	22	NA	27	20	NA	NA
Aug	22	74	23	14	12	28
Sept	41	73	29	12	16	24
ave	26	74	27	15	15	26

Dissolved organic carbon (DOC) concentrations varied from a low of 3.6 mg/L in Beaver Lake, to a high of 9.7 mg/L in Trappers Lake (St. Croix Watershed Research Station data, Table 4). Sources of DOC are both autochthonous and allochthonous in the drainage lakes, but strictly autochthonous in Trappers Lake. The DOC values measured at PIRO are high enough to attenuate light, and thus reduce photosynthesis (Schindler and Gunn 2004).

The Carlson trophic state indices (TSI; Carlson 1977) of PIRO lakes based on average chlorophyll-*a* measurements ranged from a low of 37.4 in Miners Lake to a high of 52.6 in Little Beaver Lake (Table 6). Generally, lakes with a TSI <30 are considered oligotrophic and usually have clear water, while lakes with TSI values >50 are considered eutrophic and usually have limited transparency (Wetzel 2001). Given this interpretation of the index, most of the PIRO lakes are mesotrophic, with Little Beaver being slightly eutrophic.

Carlson and Simpson (1996) define trophic state as the total algal biomass in a waterbody at a given time and location, hence the preference for calculating the index based on chlorophyll-*a*. Total phosphorus and Secchi depth may also be used to calculate TSI, however, and differences from the chlorophyll TSI may help to explain lake processes.

Total phosphorus and Secchi TSIs that are greater than the chlorophyll TSI indicate that color or particulates other than algae are limiting light penetration (Carlson and Simpson 1996), as is the case in Miners Lake. This lake is relatively tannin-stained, shallow, and subject to frequent mixing. Chlorophyll TSI values that are greater than Secchi and total phosphorus TSI values indicate that large particles, such as cyanobacteria, may dominate, and Secchi depths are greater than expected from the chlorophyll index. Both Beaver and Little Beaver Lakes reflect this situation when the average values are used, because of high chlorophyll values in May and September. When TSIs are calculated for each sampling period, however, these two lakes have substantially lower values during June and August (e.g., 32 and 36 in June, for Beaver and Little Beaver Lakes, respectively; see Appendix B for all data). Trappers Lake is shallow, with no light extinction occurring (hence, no Secchi TSI). Comparing the chlorophyll and total phosphorus TSIs, Trappers Lake may be similar to Miners Lake in that particles other than algae may dominate the water column. Chapel Lake, which is meromictic, has chlorophyll TSI values consistently higher than total phosphorus TSI values, another indication of possible phosphorus limitation. Grand Sable Lake has a stable Secchi TSI throughout the season (Appendix A), however as the season progressed, the phosphorus TSI dropped relative to the chlorophyll TSI, indicating an increased phosphorus limitation late in the season.

Table 6. Trophic state indices for lakes in Pictured Rocks National Lakeshore, 2005, calculated from seasonal average chlorophyll-*a* (chl-*a*), Secchi depth, and total phosphorus (TP) values. NA = not available.

TSI	Grand Sable	Trappers	Chapel	Beaver	Little Beaver	Miners
chl- <i>a</i>	42	42	41	47	53	37
Secchi	40	NA	42	40	45	47
TP	34	37	35	40	48	44

Profiles of temperature and dissolved oxygen concentration show all lakes well mixed during the May sampling (Appendix B), with the exception of Chapel Lake, which is meromictic. Chapel Lake had a weak thermocline in the top 5 m in May. During the June, August, and September sampling events, the thermocline in Chapel Lake was well-developed within the upper 10 m, dropping from between 20-25 °C at the surface to approximately 4 °C at 10 m. Dissolved oxygen concentrations in this lake decreased gradually to a depth of about 15 m, then rose to impossible levels (e.g., 90 mg/L) probably due to ionic interference with the probe's membrane. Miners and Trappers Lakes remained mixed throughout the season, with anoxia occurring only in the bottom 0.5 m. Similarly, Beaver and Little Beaver Lakes showed little stratification throughout the season, with the exception of the bottom 1 m. Grand Sable Lake had a well-developed thermocline by the time of the June sampling, which it maintained throughout the season. The dissolved oxygen concentration in this lake remained high throughout the profile in the June sampling, though in July, the concentration dropped abruptly below a depth of 18 m. In September, dissolved oxygen concentrations in the hypolimnion of Grand Sable Lake fell below 4 mg/L, the EPA criterion for fresh water, and the lake exhibited a typical clinograde oxygen curve.

### Sleeping Bear Dunes National Lakeshore

With the exception of Florence Lake, lakes at SLBE are generally well-buffered and hard. Measurements of specific conductance and alkalinity were relatively high. All lakes were alkaline, with average lake pH values ranging from 8.3 for Tucker Lake to 8.8 for School Lake (Table 7). Several lakes had high chloride (Cl<sup>-</sup>) and sodium (Na<sup>+</sup>) concentrations, with Round Lake having concentrations twice those of the next highest lake (School for Na<sup>+</sup> and Loon for Cl<sup>-</sup>; Table 7). These lakes are close to roads and may be receiving road salt via runoff. Calcium concentrations are high enough to support zebra mussels (*Dreissena polymorpha*) (Cohen 2004) at all lakes except Florence, and indeed, several lakes already host this exotic species. Several lakes also have relatively high sulfate (SO<sub>4</sub><sup>-2</sup>) concentrations, which is not unusual in calcareous regions (Wetzel 2001). Most of the lakes sampled at SLBE have surface water connections, with the exceptions of North Bar (which is intermittently connected to Lake Michigan), Shell, and Florence. The chemistry of Florence Lake suggests that this lake is isolated from the groundwater. Shell and North Bar Lakes likely receive water from groundwater discharge as well as the immediate catchment watershed. Round, Tucker, and at times, School and Bass Lakes receive inflow from surface water but do not have a surface outlet. These lakes likely have slower flushing rates than flow-through lakes.

Dissolved organic carbon (DOC) concentrations were highly variable, ranging from a low of 3.3 mg/L at Loon Lake to 13.4 mg/L at School Lake. Because School Lake is shallow and subject to

frequent suspension of bottom materials, DOC in this lake may be due to production by algae and macrophytes. Tucker Lake is highly stained, with DOC from allochthonous sources (Schindler and Gunn 2004).

Total nitrogen (TN) and total phosphorus (TP) values exceeded EPA criteria for Ecoregion VII in Shell and School Lakes consistently throughout the season (Table 7). (See Appendix B for all data; note that nutrient data from White Water Associates were not used, as the lab's method detection limits were too high.) Criteria for the subcoregion containing SLBE (Level III ecoregion 51) are 0.81 mg/L for TN and 20 µg/L for TP (USEPA 2000b). Chlorophyll-*a* and Secchi depth, which are considered response variables, also did not meet the USEPA criteria of 5 µg/L and 3.2 m, respectively, in several lakes on multiple occasions. Round Lake was the only lake to have Secchi depth measurements deeper than the EPA criterion consistently throughout the season.

Dissolved silica concentrations were below detection level at the beginning of the season at all lakes except North Bar and Loon (White Water Associates data, including raw samples in May). Interlaboratory comparison of dissolved silica data shows great disagreement at low levels, with better consistency at concentrations approximately  $\geq 4$  mg/L. It is possible that low silica concentrations may have affected algal community composition, especially early in the season, at several lakes.

The Carlson trophic state indices (TSI; Carlson 1977) of SLBE lakes based on average chlorophyll-*a* measurements ranged from a low of 38 in Shell Lake to a high of 49 in Florence Lake (Table 8). As explained above, lakes with a TSI  $<30$  are considered oligotrophic and usually have clear water, while lakes with TSI values  $>50$  are considered eutrophic and usually have limited transparency (Wetzel 2001). Given this interpretation of the index, all of the lakes sampled at SLBE are mesotrophic.

Table 7. Average values of field and laboratory variables measured at Sleeping Bear Dunes National Lakeshore, 2005. N = number of samples. Laboratory analyses conducted by White Water Associates and St. Croix Watershed Research Station (*italics*). When analytes were below detection limits (DL), 0.5 of DL was used in calculations. Field measurements included Secchi depth, pH, and specific conductance (EC25). Near-surface values were used for pH and specific conductance.

Variable	N	Manitou	Florence	Shell	Bass (L)	School	Tucker	North Bar	Loon	Round
Chl- <i>a</i> (µg/L)	4	3.88	6.86	2.15	3.24	4.50	3.12	4.33	3.39	3.88
TP (mg/L)	2	0.045	0.045	0.05	0.05	0.055	0.055	0.045	0.045	0.045
<i>TP</i> (µg/L)	<i>2 or 3</i>	<i>8.66</i>	<i>14.10</i>	<i>12.61</i>	<i>9.26</i>	<i>21.90</i>	<i>17.50</i>	<i>10.90</i>	<i>10.68</i>	<i>10.87</i>
TKN (mg/L)	2	0.435	0.68	0.785	0.82	0.815	0.8	0.4	0.37	0.695
<i>TN</i> (mg/L)	<i>2 or 3</i>	<i>0.41</i>	<i>0.65</i>	<i>0.96</i>	<i>0.59</i>	<i>1.08</i>	<i>0.76</i>	<i>0.51</i>	<i>0.22</i>	<i>0.56</i>
NO <sub>3</sub> /NO <sub>2</sub> - N (mg/L)	2	0.0175	0.005	0.005	0.0175	0.005	0.005	0.335	0.09	0.0045
<i>NO<sub>3</sub>/NO<sub>2</sub> - N</i> (mg/L)	<i>2</i>	<i>0.006</i>	<i>0.011</i>	<i>0.011</i>	<i>0.008</i>	<i>0.006</i>	<i>0.007</i>	<i>0.122</i>	<i>0.012</i>	<i>0.007</i>
NH <sub>4</sub> -N (mg/L)	1	0.13	0.03	0.07	0.13	0.04	0.025	0.06	0.02	0.05
DOC (mg/L)	3	7.7	8.8	9.0	9.0	11.0	11.0	4.3	4.5	7.7
<i>DOC</i> (mg/L)	<i>2 or 3</i>	<i>6.7</i>	<i>8.9</i>	<i>10.0</i>	<i>9.4</i>	<i>13.4</i>	<i>12.0</i>	<i>3.5</i>	<i>3.3</i>	<i>7.2</i>
Alkalinity (mg/L)	3 or 4	134	43.75	108.5	100.25	89.25	123	145.5	132.25	129.5
Cl (mg/L)	3	0.8	0.8	1.1	6.4	7.7	1.4	9.6	7.9	15.1
<i>Cl</i> (mg/L)	<i>2 or 3</i>	<i>0.52</i>	<i>0.75</i>	<i>1.16</i>	<i>4.51</i>	<i>9.45</i>	<i>1.26</i>	<i>4.07</i>	<i>7.87</i>	<i>18.25</i>
SO <sub>4</sub> (mg/L)	3	6.8	3.4	16.7	3.1	3.7	3.5	7.0	7.1	7.2
<i>SO<sub>4</sub></i> (mg/L)	<i>2 or 3</i>	<i>6.39</i>	<i>3.15</i>	<i>20.02</i>	<i>3.14</i>	<i>5.81</i>	<i>4.83</i>	<i>9.41</i>	<i>10.05</i>	<i>9.67</i>
Ca (mg/L)	2	33.51	12.97	32.94	31.49	24.56	35.08	44.29	41.99	29.62
Na (mg/L)	2	1.38	0.63	1.57	2.98	3.51	1.05	1.59	5.78	12.04
K (mg/L)	2	0.55	0.63	0.41	0.92	0.70	0.32	0.57	0.66	0.59
Mg (mg/L)	2	15.52	5.74	14.32	10.08	10.78	12.67	15.38	12.42	15.91
SiO <sub>2</sub> (mg/L)	2	0.1	0.1	10.7	2.7	12.5	5.8	5.4	7.8	5.7
<i>SiO<sub>2</sub></i> (mg/L)	<i>2</i>	<i>1.17</i>	<i>0.39</i>	<i>13.66</i>	<i>3.65</i>	<i>16.36</i>	<i>7.72</i>	<i>5.48</i>	<i>7.14</i>	<i>6.72</i>
Secchi depth (m)	3 or 4	2.6	2.5	3.0	3.2	NA	NA	2.2	3.2	4.6
pH (std. units)	4	8.6	8.4	8.5	8.6	8.8	8.3	8.3	8.4	8.7
EC25 (µS/cm)	4	270	111	262	229	212	262	329	310	319

Shading indicates suspect values were included in average. See Appendix A for all data.

Table 8. Trophic state indices for lakes in Sleeping Bear Dunes National Lakeshore, 2005, calculated from seasonal average chlorophyll-*a* (chl-*a*), Secchi depth, and total phosphorus (TP) values.

TSI	Manitou	Florence	Shell	Bass (L)	School	Tucker	North Bar	Loon	Round
chl- <i>a</i>	44	49	38	42	45	42	45	43	44
Secchi	46	47	44	43	58	46	48	43	38
TP	35	42	41	36	49	45	39	38	39

To help explain lake processes, we also examined TSIs calculated from TP and Secchi depth. Total phosphorus and Secchi TSIs that are greater than the chlorophyll TSI indicate that color or particulates other than algae are limiting light penetration (Carlson and Simpson 1996), as is the case in Shell, School, and Tucker Lakes. All three lakes are shallow, with frequent mixing potentially suspending particles in the water column, especially marl in Shell and School. Tucker Lake is also tannin-stained. Chlorophyll TSI values that are greater than Secchi TSI values indicate that large particles, such as cyanobacteria, may dominate, or zooplankton may have grazed the smaller particles, allowing greater transparency. Florence and Round Lakes exemplify this situation. Chlorophyll TSI values greater than phosphorus TSI values, as observed in all but the three shallowest lakes (Shell, School, and Tucker) may indicate phosphorus limitation of algae production. The TN:TP ratios indicate all SLBE lakes are phosphorus limited (Table 9), even if using the relatively high critical value of 15 by weight (Shaw et al. 1996).

Table 9. Total nitrogen to total phosphorus (TN:TP) ratios for lakes in Sleeping Bear Dunes National Lakeshore, 2005. NA = not available.

	Manitou	Florence	Shell	Bass (L)	School	Tucker	North Bar	Loon	Round
Jun	47	48	NA	69	NA	38	74	NA	NA
Aug	71	40	75	64	50	46	61	20	50
Sept	36	52	77	60	48	47	33	22	52
ave.	48	46	76	64	49	44	46	21	51

Profiles of temperature and dissolved oxygen (Appendix B) show that a thermocline had not strongly developed in any of the lakes during the May sampling. (School Lake is not included in Appendix B because it is too shallow, at <2 m, to collect profile data.) Except for Shell and Tucker Lakes, both of which are shallow, all lakes had begun to develop an oxycline in May though it was not yet strongly established. During the late June/early July and August sampling periods, most lakes had a clearly recognizable thermocline. Shell and Tucker Lakes remained fairly well-mixed throughout the season. Loon and Round Lakes had an increase in dissolved oxygen concentration slightly below the Secchi depth in early July, suggesting a deeper layer of photosynthetic activity. Several lakes had dissolved oxygen concentrations below the EPA criterion of 4 mg/L for fresh water in a substantial portion of the lake. For example, in Loon Lake, the bottom 9-10 m, or nearly half of the total depth, was below the EPA criterion in July, August, and September. Most lakes had turned over by the time of the September sampling, with

the exceptions of Lake Manitou and Loon Lake, both of which are relatively deep, and both of which maintained an anoxic layer below the thermocline.

### Comparisons of PIRO and SLBE Lakes

Lakes at SLBE had higher calcium, sodium, and magnesium concentrations and slightly lower potassium concentrations than lakes at PIRO. Specific conductance and alkalinities of lakes were higher at SLBE than at PIRO. Differences in these parameters between parks are likely due to the surrounding land and underlying rock. Substrates at SLBE are more calcareous than at PIRO. Total phosphorus concentrations were similar in the two parks, however, total nitrogen concentration at SLBE was approximately double that at PIRO. While lakes at both parks are currently phosphorus-limited, TN:TP ratios suggest lakes at PIRO may be more likely to become nitrogen-limited at some time.

Most lakes at both parks receive water from the surface and groundwater table. Florence Lake, at SLBE, seems to be the only lake that is not connected to either surface or groundwater flow.

Table 10. Mean values of measured parameters across lakes in Pictured Rocks National Lakeshore (PIRO) and Sleeping Bear Dunes National Lakeshore (SLBE), 2005. Values in standard font were measured by White Water Associates (or in the field for Secchi, pH, and EC25); values in italics were measured by St. Croix Watershed Research Station.

Parameter	PIRO (mean across lakes and season)	SLBE (mean across lakes and season)
Chl- <i>a</i> (µg/L)	4.33	3.92
TP (µg/L)	<i>12.12</i>	<i>12.76</i>
TN (mg/L)	<i>0.32</i>	<i>0.63</i>
NO <sub>3</sub> /NO <sub>2</sub> - N (mg/L)	<i>0.021</i>	<i>0.023</i>
DOC (mg/L)	7.1	8.1
DOC (mg/L)	<i>6.1</i>	8.2
Alkalinity (mg/L)	81	111
Cl (mg/L)	0.6	5.6
Cl (mg/L)	<i>0.4</i>	<i>4.6</i>
SO <sub>4</sub> (mg/L)	5.2	6.5
SO <sub>4</sub> (mg/L)	<i>6.6</i>	<i>7.5</i>
Ca (mg/L)	23.12	31.82
Na (mg/L)	1.03	3.39
K (mg/L)	0.65	0.59
Mg (mg/L)	8.19	12.53
SiO <sub>2</sub> (mg/L)	5.79	5.6
SiO <sub>2</sub> (mg/L)	<i>6.25</i>	<i>6.9</i>
Secchi depth (m)	3.3	3.0
pH (std. units)	8.1	8.5
EC25 (µS/cm)	176	256

## Summary

Water quality data collected in 2005 show that several lakes in both Pictured Rocks and Sleeping Bear Dunes National Lakeshores do not meet their respective ecoregion criteria for total phosphorus and total nitrogen. Reasons for these exceedences should be explored and management actions that curtail inputs of these nutrients should be taken, if possible. Most of the lakes had no development along the shoreline, so inputs of nutrients were from the larger watershed and the atmosphere. Most of the lakes in both parks are mesotrophic with the exception of Little Beaver Lake at PIRO, which is slightly eutrophic. All of the lakes sampled were phosphorus limited.

## Future Monitoring

When the Network completes the water quality monitoring protocol for inland lakes, some aspects of what was done this initial year are likely to remain the same and some are likely to change. We expect the variables measured to remain the same, but the frequency of sampling to drop to three times in the summer (probably early June, late July, and early to mid-September). Budget constraints may limit the number of lakes we sample in subsequent years and we will likely select a subset of lakes at each park for long-term monitoring.

## Park Support

Park support was crucial during this initial year of sampling. Both parks provided boats and canoes; SLBE provided transportation across Lake Michigan waters to and from South and North Manitou Islands. The parks provided refrigerator and freezer space, laboratory space for processing samples and calibrating sondes, some lab equipment, and general space for organizing supplies and completing paperwork. Park housing was available to Network staff at low cost. Park staff were available to conduct sampling; the Network paid their salaries when they worked on this project.

At SLBE, a wilderness exemption was granted, allowing the use of a garden cart to haul heavy equipment for coring of Lake Manitou on North Manitou Island.

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## **Appendix A**

**Laboratory and field data from Pictured Rocks National Lakeshore and Sleeping Bear Dunes National Lakeshore, 2005**

Laboratory results for lakes at Pictured Rocks National Lakeshore, 2005. Analyses by White Water Associates. Values in italics are below detection limits; 1/2 of detection limit entered. DL = method detection limit; RL = reporting limit. May SiO<sub>2</sub> values not included in averages because samples were raw instead of filtered.

Parameter	DL	RL	Month	Grand Sable	Trappers	Chapel	Beaver	Little Beaver	Miners
Alkalinity (mg/L)	5	20	May	43	71	66	71	54	128
			Jun	41	74	84	77	61	153
			Aug	50	68	96	78	77	147
			Sept	50	67	98	77	74	139
			ave	46	70	86	76	66	142
NH <sub>4</sub> -N (mg/L)	0.05	0.2	May	0.06	0.11	0.09	0.07	0.07	0.13
Ca (mg/L)	0.06	0.2	May	14.15	25.14	19.39	25.36	18.37	31.4
			Aug	14.03	21.38	24.43	26.64	23	34.14
			ave	14.09	23.26	21.91	26	20.685	32.77
Cl (mg/L)	0.5	2	May	0.6	0.3	0.5	0.4	0.5	1.2
			Jun	0.4	0.4	0.4	0.4	0.4	1.5
			Aug	0.6	0.5	0.6	0.6	0.6	1.6
			ave	0.5	0.4	0.5	0.5	0.5	1.4
Chl-a (ug/L)	1	2	May	5.092	2.211	3.230	9.777	15.494	0.663
			Jun	1.242	4.114	2.322	1.109	1.782	3.270
			Aug	3.246	3.109	2.189	3.402	4.279	2.153
			Sept	3.755	3.707	3.839	6.096	16.031	1.876
			ave	3.334	3.285	2.895	5.096	9.397	1.991
Mg (mg/L)	0.06	0.2	May	4.91	5.39	9.32	5.36	5.14	16.00
			Aug	5.27	5.64	11.65	5.56	6.34	17.66
			ave	5.09	5.52	10.49	5.46	5.74	16.83
NO <sub>3</sub> /NO <sub>2</sub> (mg/L)	0.01	0.2	May	0.05	0.005	0.02	0.02	0.4	0.21
			Jun	0.005	0.005	0.005	0.005	0.005	0.22
			ave	0.03	0.01	0.01	0.01	0.20	0.22
K (mg/L)	0.06	0.2	May	0.69	0.48	0.59	0.57	0.59	0.53
			Aug	0.80	0.70	0.76	0.67	0.67	0.73
			ave	0.75	0.59	0.68	0.62	0.63	0.63
SiO <sub>2</sub> (mg/L)	0.2	2	May	4.2	0.1	3.1	7.2	7.2	3.9
			Jun	4.4	2.9	4.6	7.8	6.2	6.2
			Sept	4.4	5.5	4.2	9.1	7.5	6.7
			ave	4.4	4.2	4.4	8.5	6.9	6.5
Na (mg/L)	0.06	0.2	May	0.87	0.92	0.68	1.00	0.91	1.19
			Aug	0.98	1.20	0.91	1.17	1.14	1.40
			ave	0.93	1.06	0.80	1.09	1.03	1.30
SO <sub>4</sub> (mg/L)	2	10	May	4	0.1	6	1	0.7	4
			Jun	4.1	4.2	7.4	6	6.5	6
			Sept	4.74	4.42	10.30	5.93	8.29	9.24
			ave	4.28	3.21	7.90	4.31	5.16	6.41
DOC (mg/L)	0.31	1	May	7.6	8.5	9.2	5.2	7.7	9
			Jun	6.1	8.8	7.8	4.3	5.8	4.9
			Sept	5.7	9.4	8.2	4.5	6.8	8.3
			ave	6.5	8.9	8.4	4.7	6.8	7.4
TP (mg/L)	0.01	0.2	May	0.03	0.02	0.005	0.04	0.05	0.005
			Jun	0.04	0.06	0.03	0.04	0.04	0.04
			ave	0.04	0.04	0.02	0.04	0.05	0.02
TKN (mg/L)	0.05	0.2	May	0.35	0.59	0.34	0.08	0.47	0.39
			Jun	0.37	0.91	0.37	0.32	0.36	0.46
			ave	0.36	0.75	0.36	0.20	0.42	0.43

Laboratory results for lakes at Pictured Rocks National Lakeshore, 2005. Analyses by St. Croix Watershed Research Station.

<b>Parameter</b>	<b>Low Range</b>	<b>High Range</b>	<b>Month</b>	<b>Grand Sable</b>	<b>Trappers</b>	<b>Chapel</b>	<b>Beaver</b>	<b>Little Beaver</b>	<b>Miners</b>
Cl (mg/L)	0.025-200		Jun	0.298		0.258	0.384		
			Aug	0.309	0.298	0.276	0.367	0.273	1.329
			Sept	0.300	0.268	0.296	0.363	0.308	1.158
			ave	0.302	0.283	0.277	0.371	0.290	1.243
NO <sub>3</sub> /NO <sub>2</sub> -N (mg/L)	0.003-0.1	0.1-20	Jun	0.022		0.018	0.013		
			Aug	0.0027	0.0077	0.0007	0.0039	0.0010	0.0899
			Sept	0.0002	0.0123	0.0288	0.0020	0.0082	0.1040
			ave	0.0082	0.0100	0.0157	0.0062	0.0046	0.0970
SiO <sub>2</sub> (mg/L)	0.2-20		Aug	4.782	5.858	4.017	8.806	5.990	6.328
			Sept	4.715	5.911	4.807	9.780	7.057	6.864
			ave	4.749	5.885	4.412	9.293	6.523	6.596
SO <sub>4</sub> (mg/L)	0.025-200		Jun	4.424		6.364	7.770		
			Aug	4.531	4.448	8.453	6.250	6.844	7.672
			Sept	4.470	4.442	10.107	5.915	8.199	9.141
			ave	4.47	4.45	8.31	6.65	7.52	8.41
DOC (mg/L)	0.1-20		Jun	6.0		8.3	3.4		
			Aug	5.6	8.7	6.6	3.9	5.1	4.4
			Sept	5.3	10.8	7.2	3.4	5.9	6.9
			ave	5.6	9.7	7.3	3.6	5.5	5.6
TP (µg/L)	5-2000		Jun	9.398		8.771	9.575		
			Aug	9.878	10.051	7.191	11.046	18.063	12.499
			Sept	5.065	9.940	9.766	16.031	24.331	20.178
			ave	8.114	9.996	8.576	12.217	21.197	16.339
TN (mg/L)	0.1-20	0.2-20	Jun	0.20		0.24	0.20		
			Aug	0.21	0.75	0.16	0.16	0.22	0.34
			Sept	0.214	0.72	0.29	0.19	0.40	0.49
			ave	0.21	0.74	0.23	0.18	0.31	0.42

Field measurements for lakes at Pictured Rocks National Lakeshore, 2005. Near-surface values used for specific conductivity and pH. See Appendix B for temperature and dissolved oxygen profiles.

<b>Parameter</b>	<b>Month</b>	<b>Grand</b>			<b>Little</b>		
		<b>Sable</b>	<b>Trappers</b>	<b>Chapel</b>	<b>Beaver</b>	<b>Beaver</b>	<b>Miners</b>
Specific conductivity ( $\mu\text{S/cm}$ )	May	93	136	139	141		231
	Jun	99	139	165	148	134	271
	Aug	120	158	222	181	179	310
	Sept	128	158	221	186	182	300
	ave	110	148	187	164	165	278
pH	May	7.46	8.14	7.63	8.06		7.36
	Jun	8.13	8.69	8.29	8.29	8.08	8.16
	Aug	8.29	8.72	8.30	8.31	8.20	8.16
	Sept	8.05	8.55	8.10	8.19	8.28	7.41
	ave	7.98	8.53	8.08	8.21	8.19	7.77
Secchi depth (m)	May	3.25	bottom	3.10	3.50	1.73	2.46
	Jun	4.22	bottom	3.25	3.85	2.80	2.18
	Aug	4.40	bottom	4.38	4.25	2.50	3.29
	Sept	3.75	bottom	3.62	4.05	4.12	1.97
	ave	3.91	bottom	3.59	3.91	2.79	2.48

Laboratory results for lakes at Sleeping Bear Dunes National Lakeshore, 2005. Analyses by White Water Associates. Italicized values indicate results below detection limits; 1/2 of detection limit entered. DL = method detection limit; RL = reporting limit. May SiO<sub>2</sub> values not included in averages because samples were raw instead of filtered.

Parameter	DL	RL	Month	Manitou	Florence	Shell	Bass (L)	School	Tucker	North Bar	Loon	Round
Alkalinity (mg/L)	5	20	May	137	42	118	109	102	124	155	147	138
			Jun/Jul	142	44	108	104	92	124	128	136	158
			Aug	123	48	98	98	75	118	148	120	110
			Sept	12.5	41	110	90	88	126	151	126	112
			ave	134	44	109	100	89	123	146	132	130
NH <sub>4</sub> -N (mg/L)	0.05	0.2	May	0.13	0.03	0.07	0.13	0.04	0.025	0.06	0.02	0.05
Ca (mg/L)	0.06	0.2	May	36.58	12.36	37.9	35.21	32.28	38.88	48.02	47.82	35.60
			Aug	30.44	13.57	27.98	27.76	16.83	31.28	40.55	36.16	23.64
			ave	33.51	12.97	32.94	31.49	24.56	35.08	44.29	41.99	29.62
Cl (mg/L)	0.5	2	May	0.8	0.7	1.0	6.0	5.7	1.3	3.9	7.6	19.5
			Jun/Jul	0.8	0.9	1.1	6.5	7.8	1.4	20.6	8.3	6.8
			Sept	0.8	0.8	1.3	6.6	9.5	1.6	4.4	7.7	19.0
			ave	0.8	0.8	1.1	6.4	7.7	1.4	9.6	7.9	15.1
Chl-a (ug/L)	1	2	May	5.646	4.641	2.932	2.799	3.534	1.929	2.534	2.321	2.402
			Jun/Jul	3.128	4.739	1.773	4.519	2.667	3.028	5.334	4.695	5.404
			Aug	2.695	11.513	2.697	3.707	7.301	4.595	2.790	2.951	5.404
			Sept	4.047	6.565	1.205	1.938	4.484	2.914	6.660	3.604	2.301
			ave	3.879	6.865	2.152	3.241	4.497	3.117	4.330	3.393	3.878
Mg (mg/L)	0.06	0.2	May	15.31	5.69	13.54	9.86	9.56	11.80	15.19	12.52	15.12
			Aug	15.72	5.78	15.10	10.30	11.99	13.53	15.57	12.31	16.70
			ave	15.52	5.74	14.32	10.08	10.78	12.67	15.38	12.42	15.91
NO <sub>3</sub> /NO <sub>2</sub> (mg/L)	0.01	0.2	May	0.03	0.005	0.005	0.03	0.005	0.005	0.42	0.17	0.004
			Jun/Jul	0.005	0.005	0.005	0.005	0.005	0.005	0.25	0.01	0.005
			ave	0.018	0.005	0.005	0.018	0.005	0.005	0.335	0.090	0.005
K (mg/L)	0.06	0.2	May	0.52	0.60	0.40	0.91	0.74	0.40	0.54	0.66	0.58
			Aug	0.58	0.65	0.41	0.93	0.66	0.24	0.59	0.65	0.60
			ave	0.55	0.63	0.41	0.92	0.70	0.32	0.57	0.66	0.59

Laboratory results from White Water Associates, continued.

Parameter	DL	RL	Month	Manitou	Florence	Shell	Bass (L)	School	Tucker	North Bar	Loon	Round
SiO <sub>2</sub> (mg/L)	0.2	2	May	0.1	0.1	0.1	0.1	0.1	0.1	6	6.9	0.1
			Jun/Jul	0.1	0.1	5.6	0.1	6	4.1	3.9	6.3	3.8
			Sept	0.1	0.1	15.7	5.2	18.9	7.4	6.9	9.2	7.6
			ave	0.1	0.1	10.7	2.7	12.5	5.8	5.4	7.8	5.7
Na (mg/L)	0.06	0.2	May	1.25	0.56	1.34	2.76	2.82	1.00	1.48	5.76	11.88
			Aug	1.50	0.70	1.80	3.20	4.20	1.10	1.70	5.80	12.20
			ave	1.38	0.63	1.57	2.98	3.51	1.05	1.59	5.78	12.04
SO <sub>4</sub> (mg/L)	2	10	May	4	1	13	1	1	1	3	2	3
			Jun/Jul	8	4.6	17	4	4.1	4.7	9.1	9.4	9.2
			Sept	8.31	4.48	20	4.33	6.1	4.77	8.81	9.83	9.26
			ave	6.8	3.4	16.7	3.1	3.7	3.5	7.0	7.1	7.2
DOC (mg/L)	0.31	1	May	8	8.3	8.1	8.5	8.9	9.1	3.8	4.7	6.8
			Jun/Jul	7.6	10	8.8	8.8	10	11	4.4	4.4	7.5
			Sept	7.4	8	10	9.6	14	13	4.8	4.5	8.8
			ave	7.7	8.8	9.0	9.0	11.0	11.0	4.3	4.5	7.7
TP (mg/L)	0.01	0.2	May	0.05	0.05	0.06	0.06	0.07	0.07	0.06	0.06	0.05
			Jun/Jul	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.04
			ave	0.05	0.05	0.05	0.05	0.06	0.06	0.05	0.05	0.05
TKN (mg/L)	0.05	0.1	May	0.41	0.77	0.77	1	0.92	0.68	0.37	0.41	0.77
			Jun/Jul	0.46	0.59	0.8	0.64	0.71	0.92	0.43	0.33	0.62
			ave	0.44	0.68	0.79	0.82	0.82	0.80	0.40	0.37	0.70

stippled value not used in average; decimal place must be off

shaded values included in average, but numbers possibly switched?

Laboratory results for lakes at Sleeping Bear Dunes National Lakeshore, 2005. Analyses by St. Croix Watershed Research Station.

Parameter	Low Range	High Range	Month	Manitou	Florence	Shell	Bass (L)	School	Tucker	North Bar	Loon	Round
Cl (mg/L)	0.025-200		Jun/Jul	0.319	0.532		0.254		1.221	4.003		
			Aug	0.671	0.800	1.159	6.532	9.066	1.232	4.148	8.021	18.660
			Sept	0.563	0.905	1.123	6.750	9.826	1.324	4.050	7.721	17.845
			ave	0.517	0.746	1.159	4.512	9.446	1.259	4.067	7.871	18.252
NO <sub>3</sub> /NO <sub>2</sub> -N (mg/L)	0.003-0.1	0.1-20	Jun/Jul	0.014	0.020		0.012		0.012	0.201		
			Aug	0.0026	0.0064	0.0090	0.0034	0.0060	0.0036	0.1021	0.0028	0.0055
			Sept	0.0017	0.0080	0.0132	0.0081	0.0058	0.0050	0.0631	0.0218	0.0078
			ave	0.006	0.011	0.011	0.008	0.006	0.007	0.122	0.012	0.007
SiO <sub>2</sub> (mg/L)	0.2-20		Aug	1.03	0.44	13.10	3.05	14.90	8.21	4.58	6.37	6.72
			Sept	1.31	0.34	14.22	4.25	17.82	7.23	6.39	7.91	6.72
			ave	1.17	0.39	13.66	3.65	16.36	7.72	5.48	7.14	6.72
SO <sub>4</sub> (mg/L)	0.025-200		Jun/Jul	2.263	0.625		0.872		4.812	9.587		
			Aug	8.461	4.274	19.510	4.160	5.445	4.848	9.664	10.182	9.749
			Sept	8.451	4.547	20.536	4.383	6.175	4.815	8.990	9.913	9.588
			ave	6.392	3.149	20.023	3.138	5.810	4.825	9.414	10.047	9.668
DOC (mg/L)	0.1-20		Jun/Jul	7.22	9.96		9.19		11.25	3.64		
			Aug	6.54	8.82	9.32	9.37	12.47	12.43	3.40	3.36	7.36
			Sept	6.29	7.92	10.64	9.53	14.31	12.37	3.55	3.21	6.98
			ave	6.68	8.90	9.98	9.36	13.39	12.02	3.53	3.28	7.17
TP (µg/L)	5-2000		Jun/July	9.178	12.618		8.854		17.699	5.887		
			Aug	5.609	17.117	12.392	8.853	21.415	16.962	7.207	11.035	11.690
			Sept	11.201	12.577	12.831	10.065	22.378	17.845	19.602	10.324	10.057
			ave	8.663	14.104	12.611	9.257	21.896	17.502	10.899	10.679	10.874
TN (mg/L)	0.1-20	0.2-20	Jun/July	0.43	0.60		0.61		0.68	0.44		
			Aug	0.40	0.69	0.93	0.57	1.07	0.78	0.44	0.22	0.59
			Sept	0.41	0.65	0.99	0.61	1.08	0.84	0.64	0.23	0.53
			ave	0.41	0.65	0.96	0.59	1.08	0.76	0.51	0.22	0.56

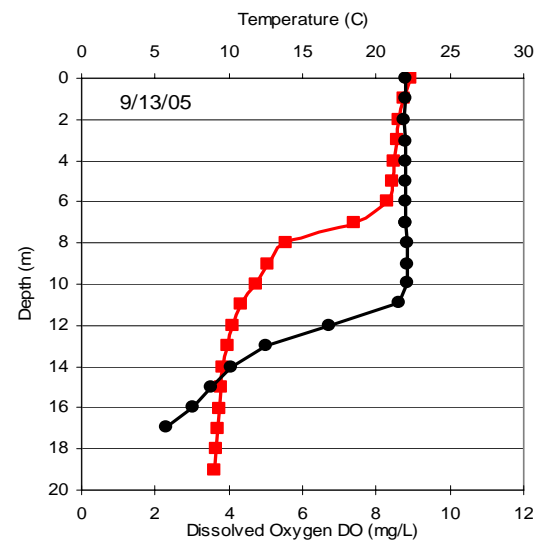
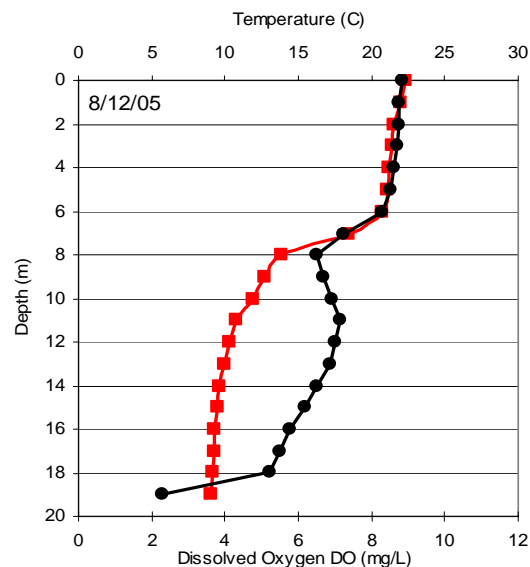
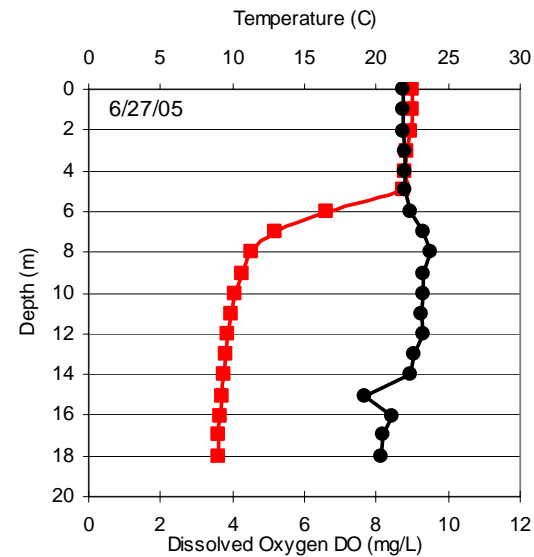
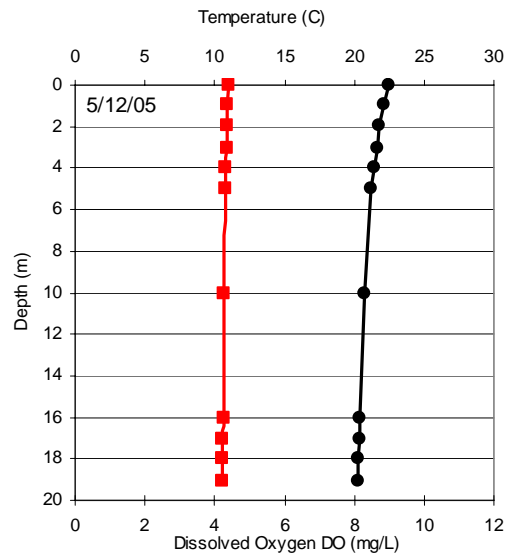
Field measurements for lakes at Sleeping Bear Dunes National Lakeshore, 2005. Near-surface values used for specific conductivity and pH. See Appendix B for temperature and dissolved oxygen profiles.

Parameter	Month	Manitou	Florence	Shell	Bass (L)	School	Tucker	North Bar	Loon	Round
Specific conductivity (μS/cm)	May	298	110	296	262	245	282	368	351	371
	Jun/Jul	276	107	249	233	202	251	325	309	322
	Aug	255	114	247	217	184	250	310	290	298
	Sept	252	113	256	203	216	266	312	291	283
	ave	270	111	262	229	212	262	329	310	319
pH	May	8.52	8.29	8.39	8.58	8.5	8.29	8.35	8.38	8.48
	Jun/Jul	8.67	8.63	8.66	8.72	9	8.49	8.43	8.57	8.72
	Aug	8.75	8.68	8.71	8.82	9.49	8.46	8.38	8.51	8.87
	Sept	8.41	8.09	8.38	8.43	8.36	8.14	8.17	8.28	8.68
	ave	8.59	8.42	8.54	8.64	8.84	8.35	8.33	8.44	8.69
Secchi depth (m)	May	1.95	3.3	bottom	3.4	bottom	bottom	3.15	2.85	4.85
	Jun/Jul	1.98	2	3.92	2.7	bottom	2.55	1.62	3.2	4.2
	Aug	3.22	1.95	2.46	2.81	1.13	bottom	2.45	2.82	4.62
	Sept	3.4	2.7	2.66	4.04	bottom	2.6	1.72	3.96	4.65
	ave	2.6	2.5	3.0	3.2	1.1	2.6	2.2	3.2	4.6

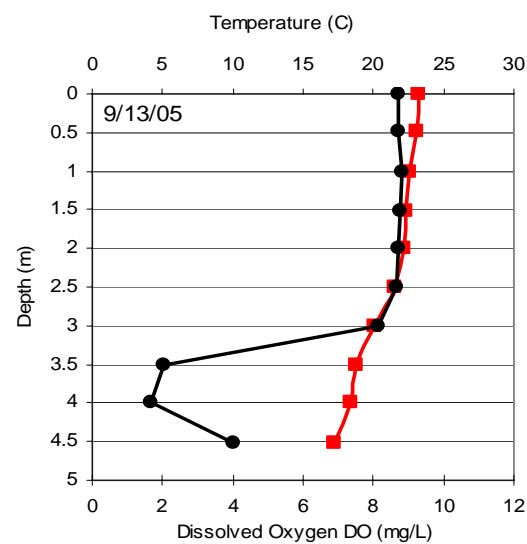
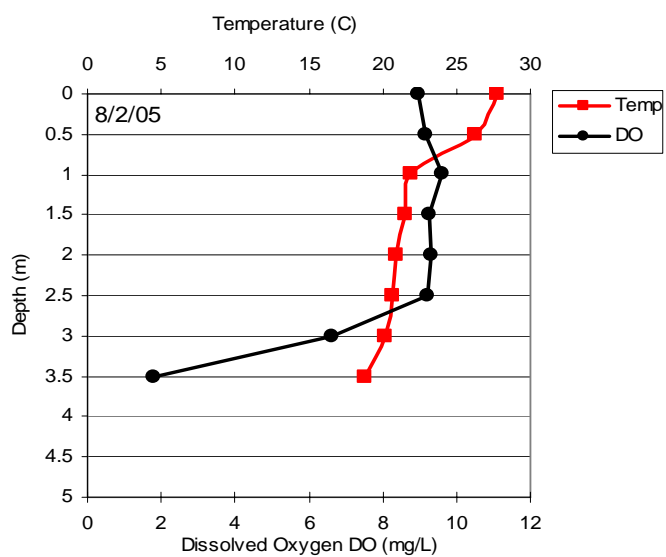
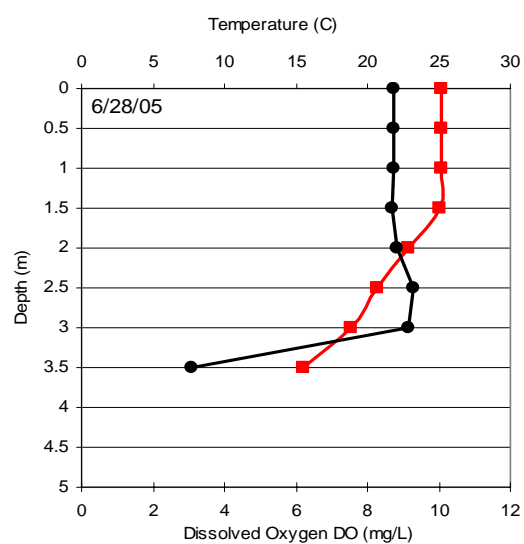
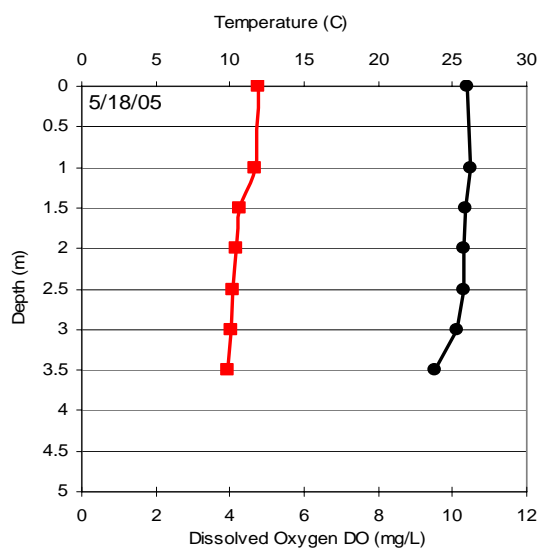
## **Appendix B**

**Temperature and oxygen profiles for inland lakes at Pictured Rocks National Lakeshore and Sleeping Bear Dunes National Lakeshore, 2005**

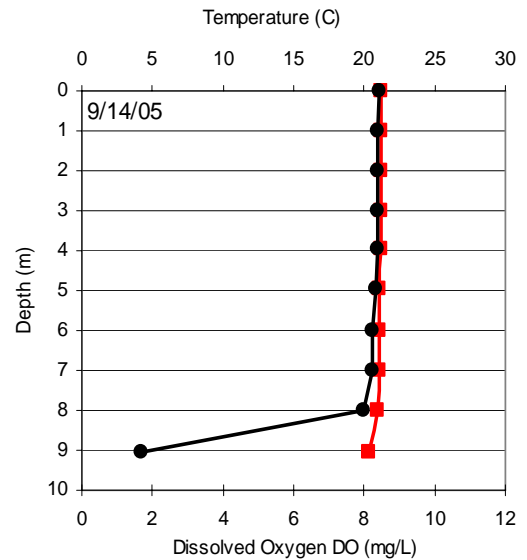
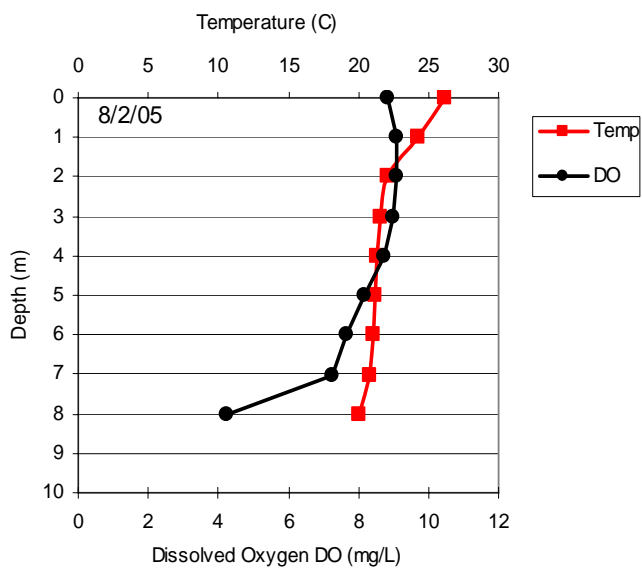
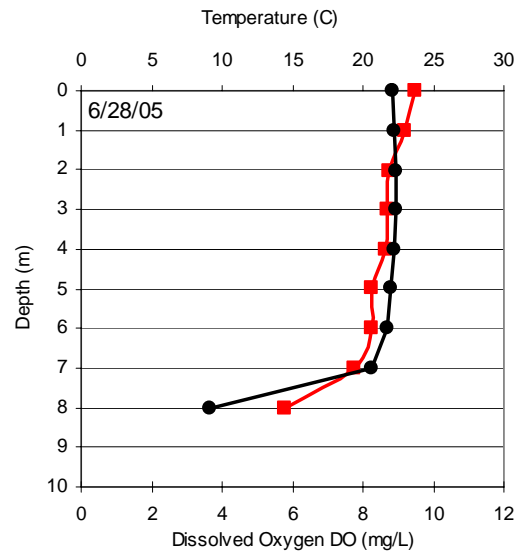
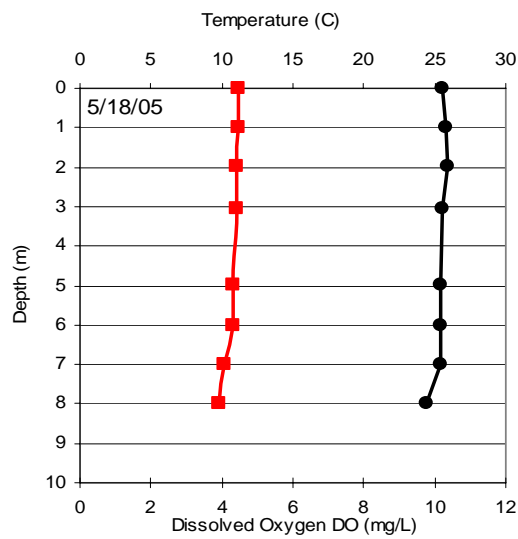
Temperature and dissolved oxygen profiles from Grand Sable Lake, Pictured Rocks National Lakeshore, 2005.



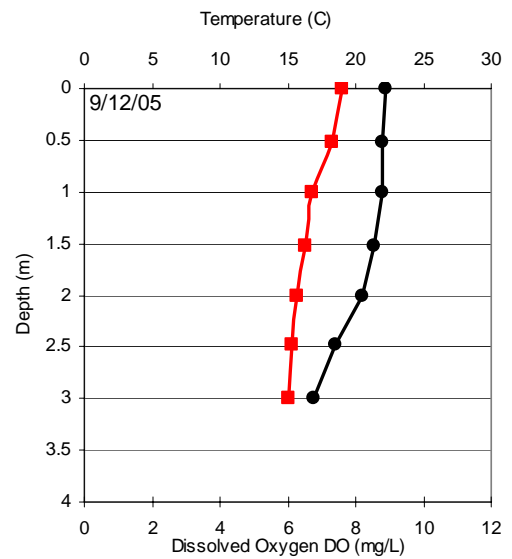
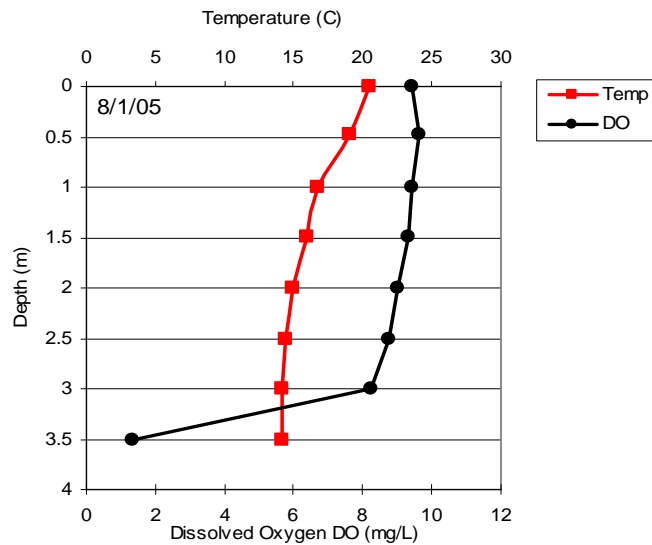
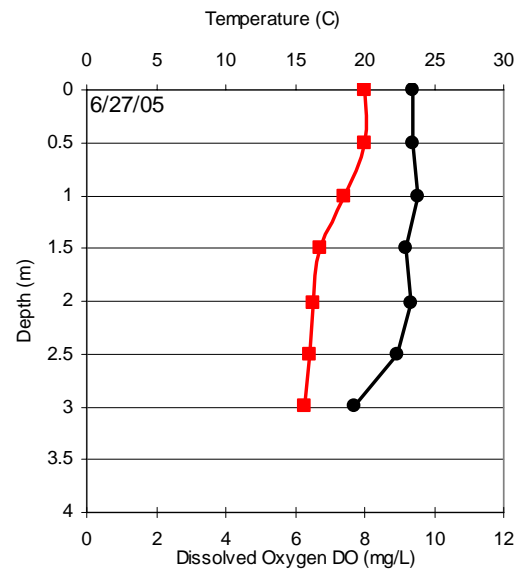
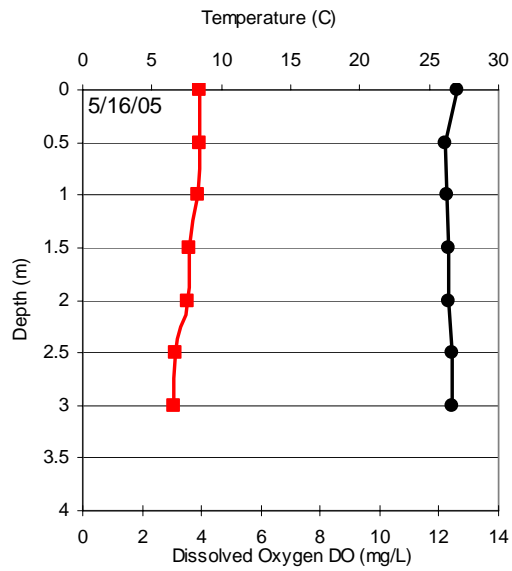
Temperature and dissolved oxygen profiles from Little Beaver Lake, Pictured Rocks National Lakeshore, 2005.



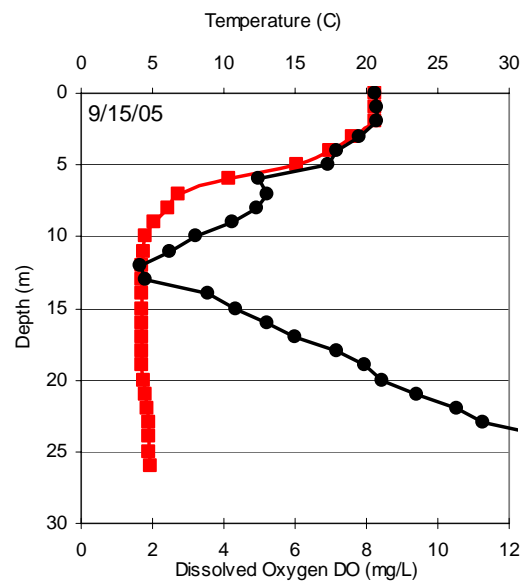
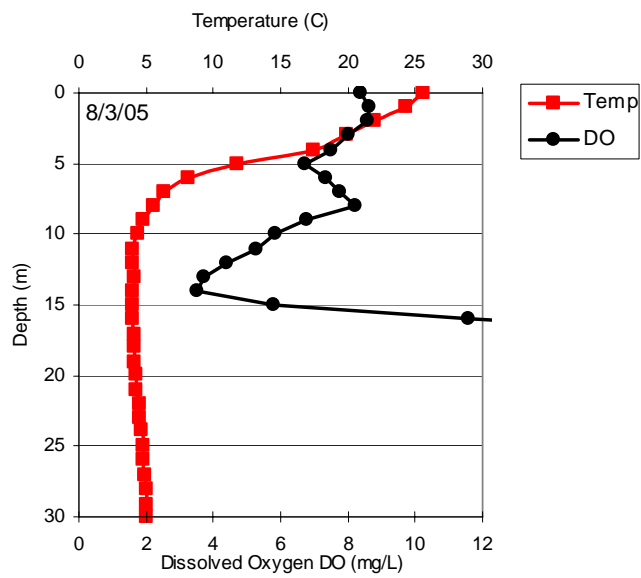
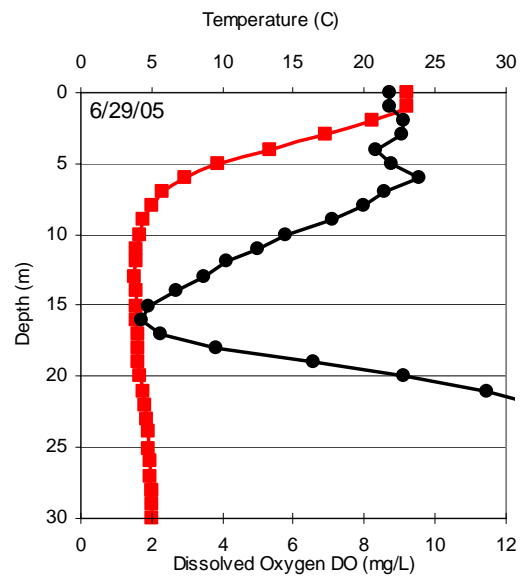
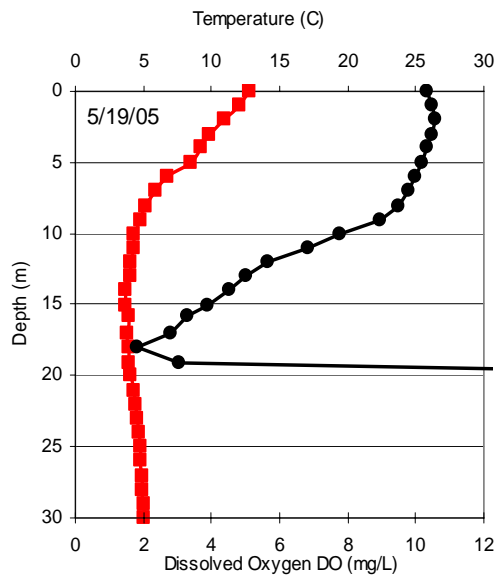
Temperature and dissolved oxygen profiles from Beaver Lake, Pictured Rocks National Lakeshore, 2005.



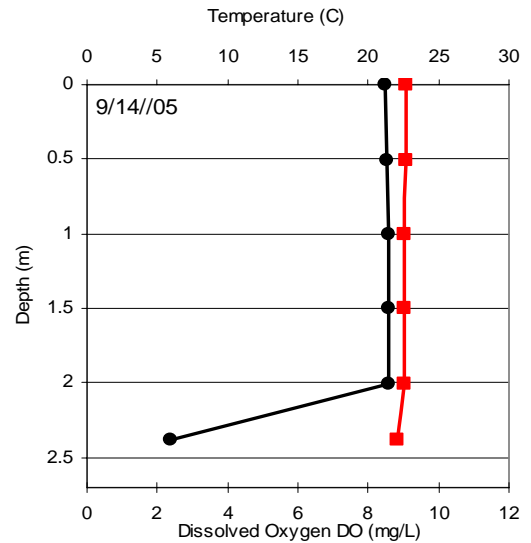
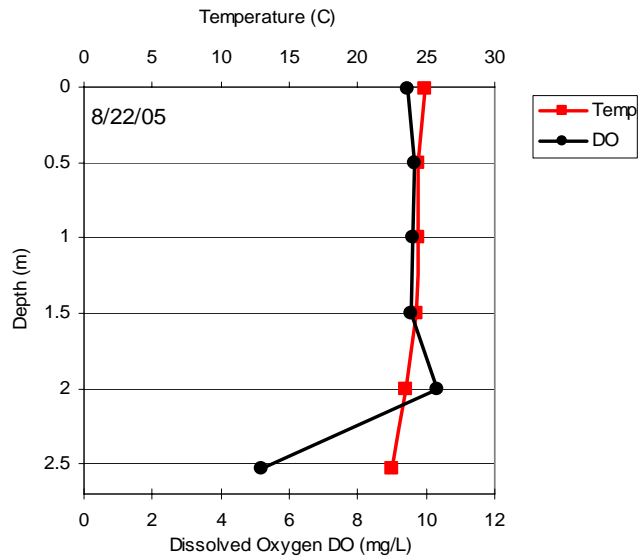
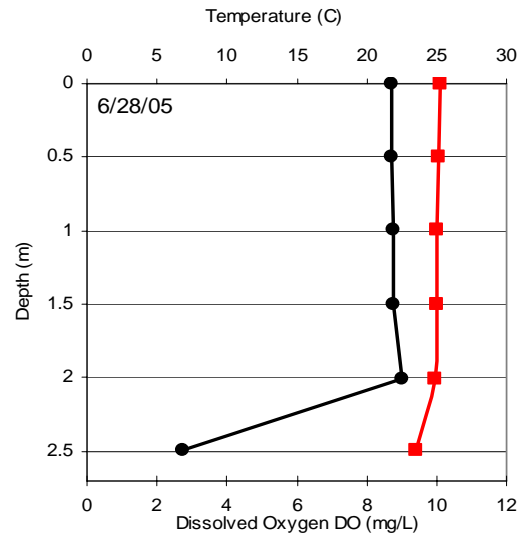
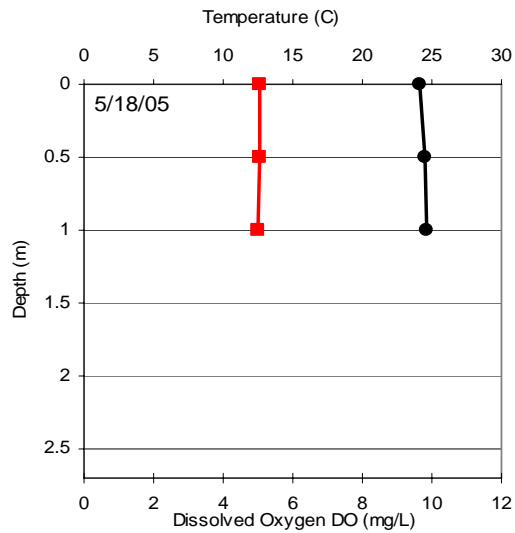
Temperature and dissolved oxygen profiles from Miners Lake, Pictured Rocks National Lakeshore, 2005.



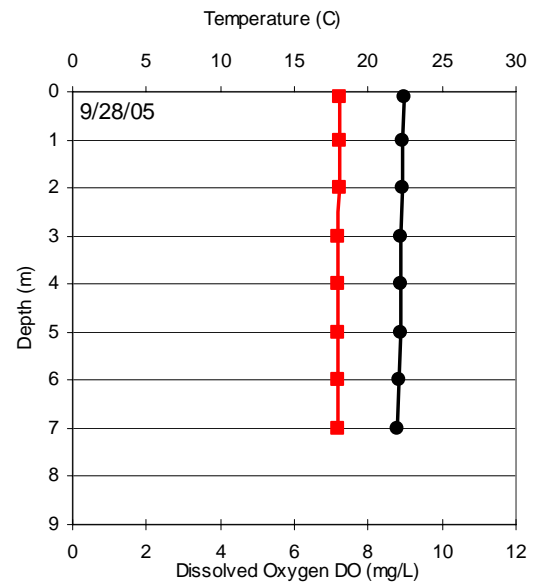
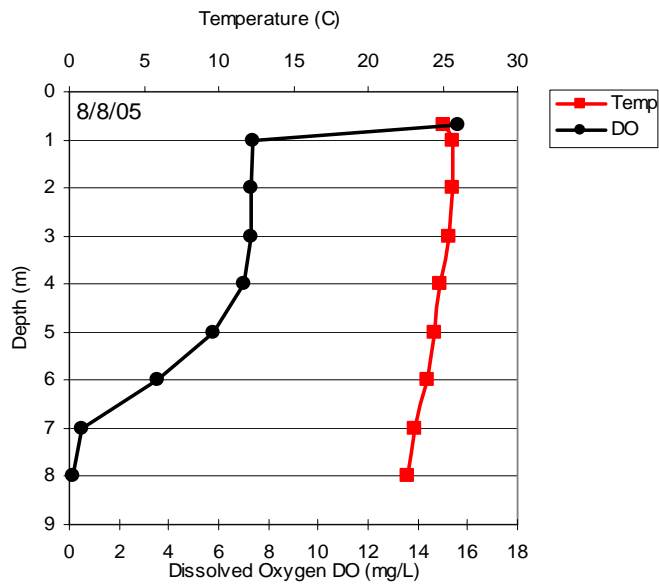
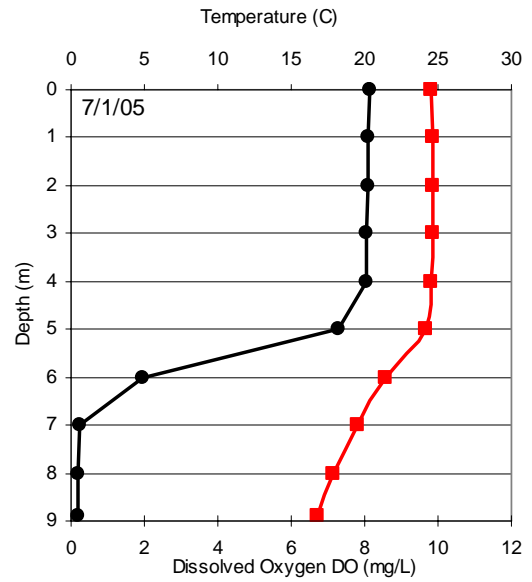
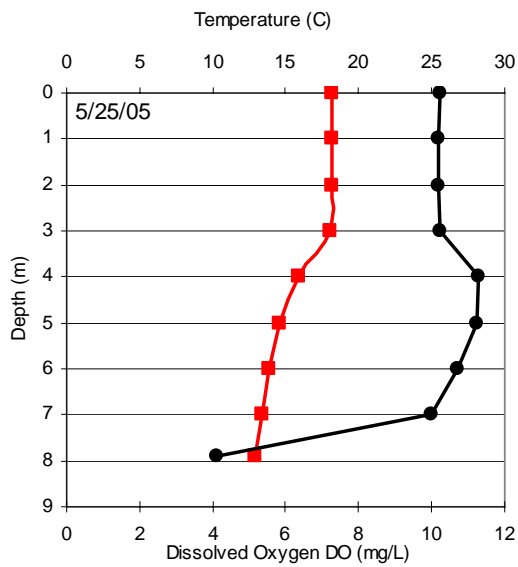
Temperature and dissolved oxygen profiles from Chapel Lake, Pictured Rocks National Lakeshore, 2005.



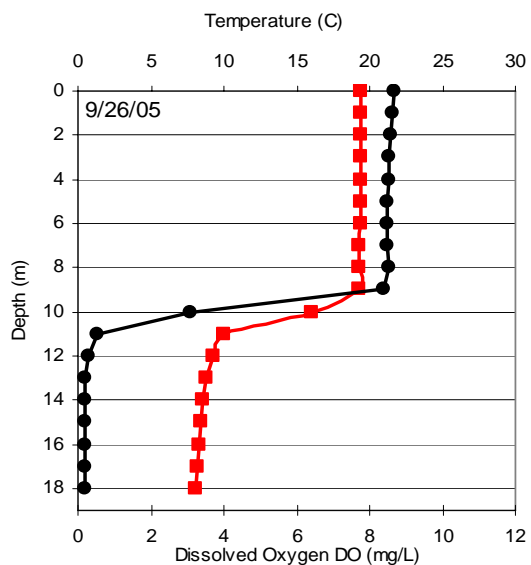
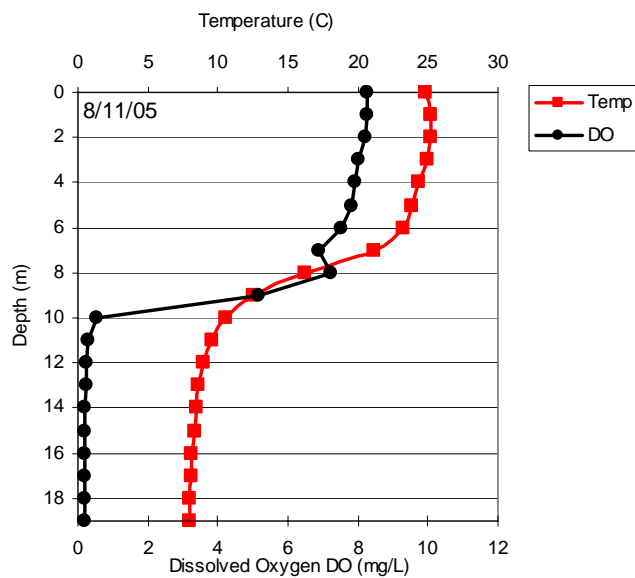
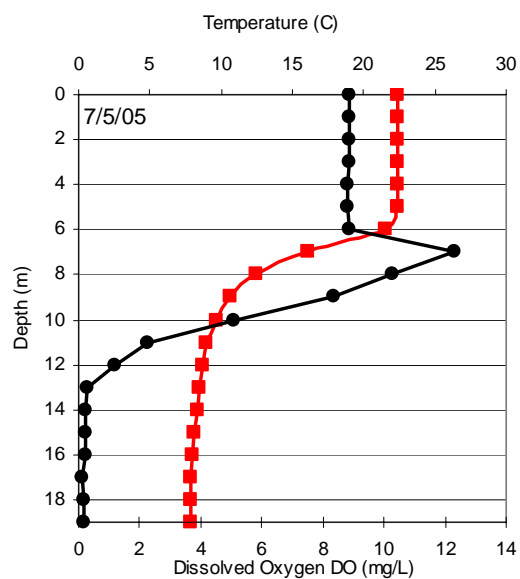
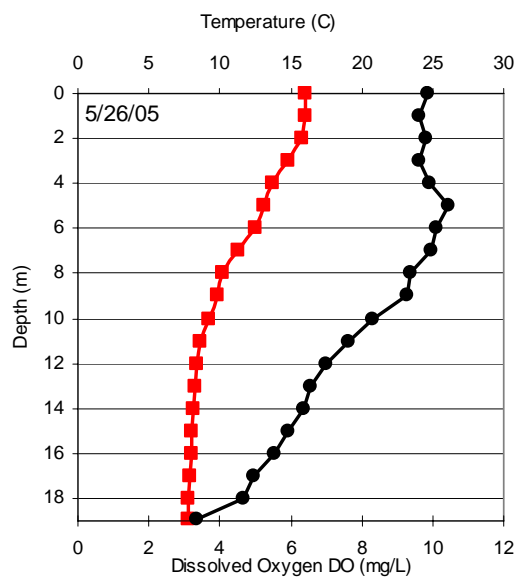
Temperature and dissolved oxygen profiles from Trappers Lake, Pictured Rocks National Lakeshore, 2005.



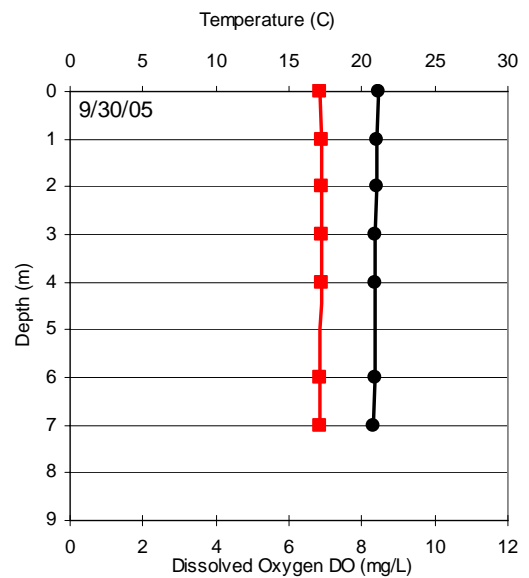
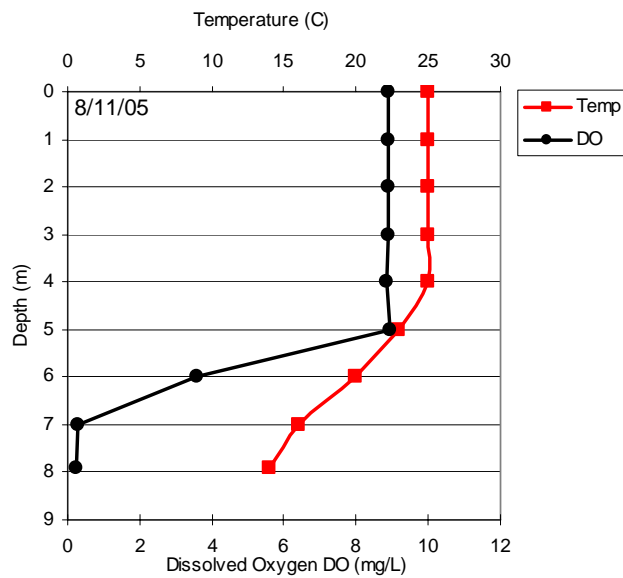
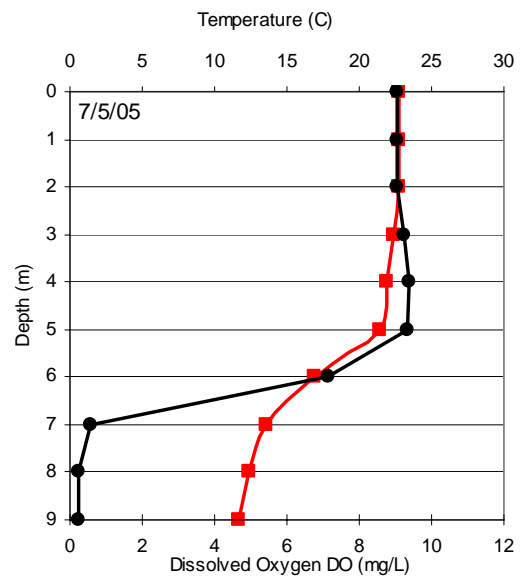
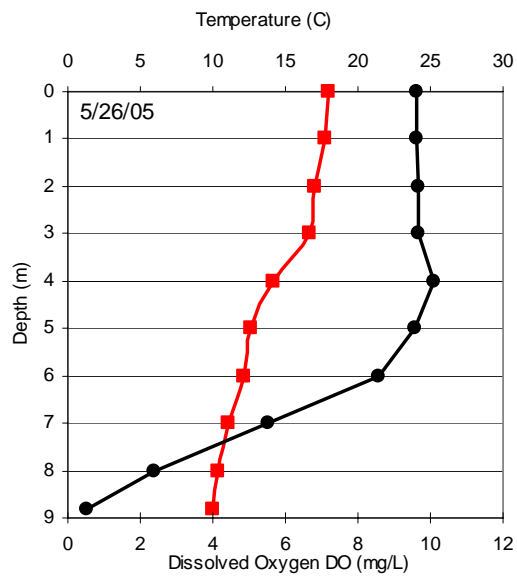
Temperature and dissolved oxygen profiles from Bass Lake (Leelenau), Sleeping Bear Dunes National Lakeshore, 2005.



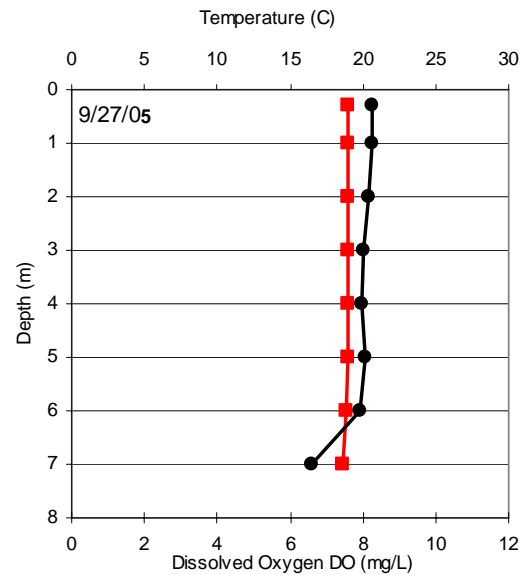
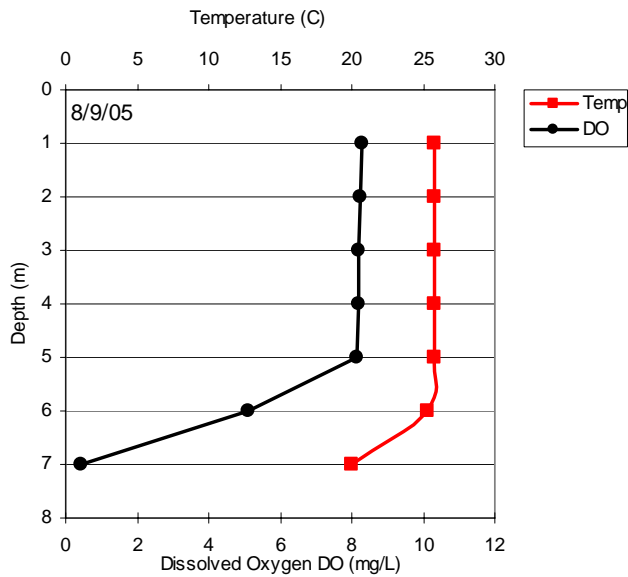
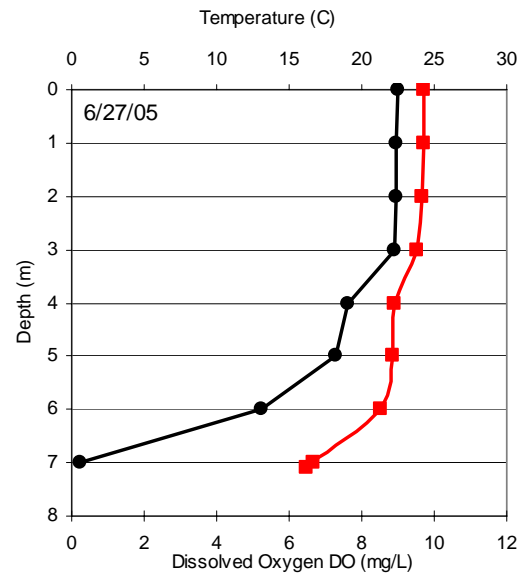
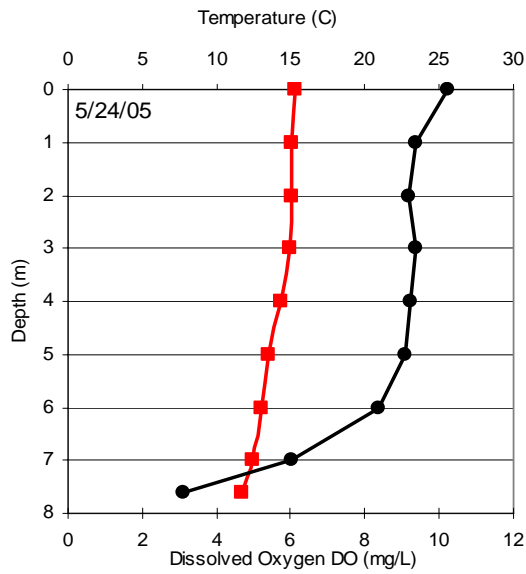
Temperature and dissolved oxygen profiles from Loon Lake, Sleeping Bear Dunes National Lakeshore, 2005.



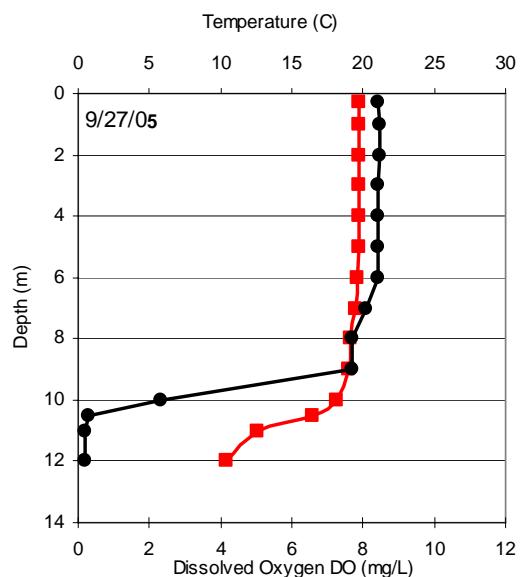
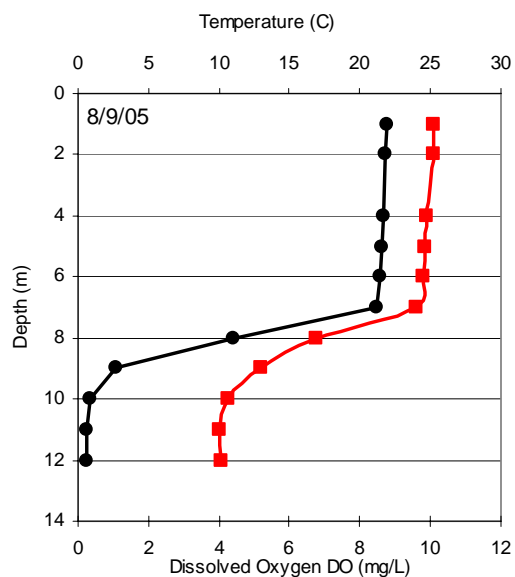
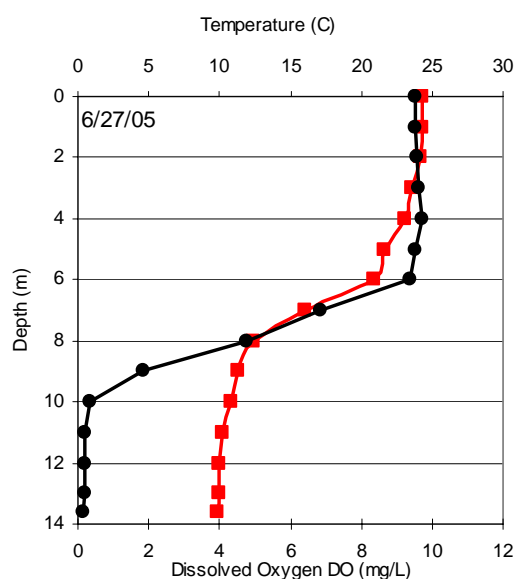
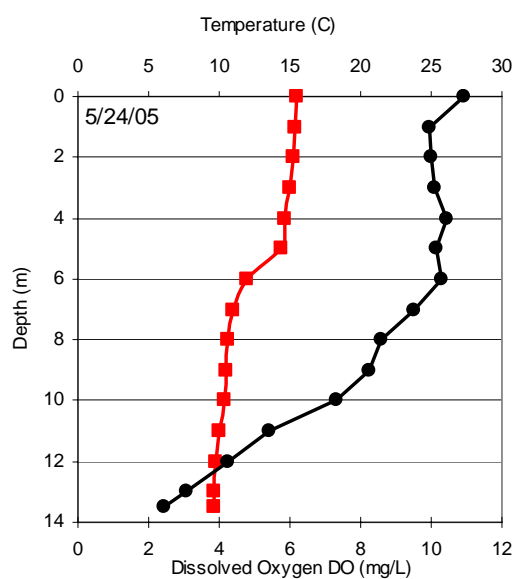
Temperature and dissolved oxygen profiles from North Bar Lake, Sleeping Bear Dunes National Lakeshore, 2005.



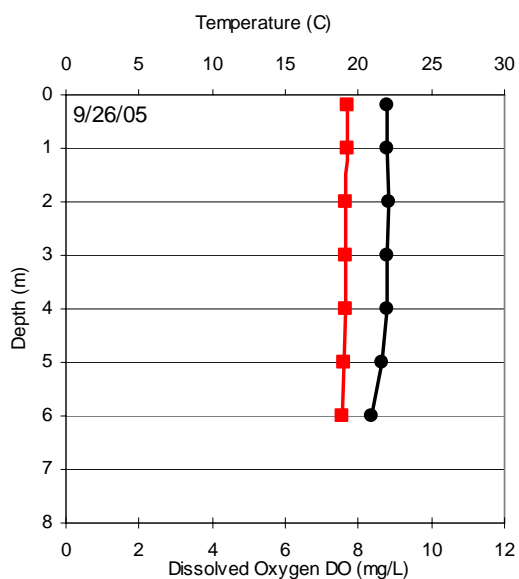
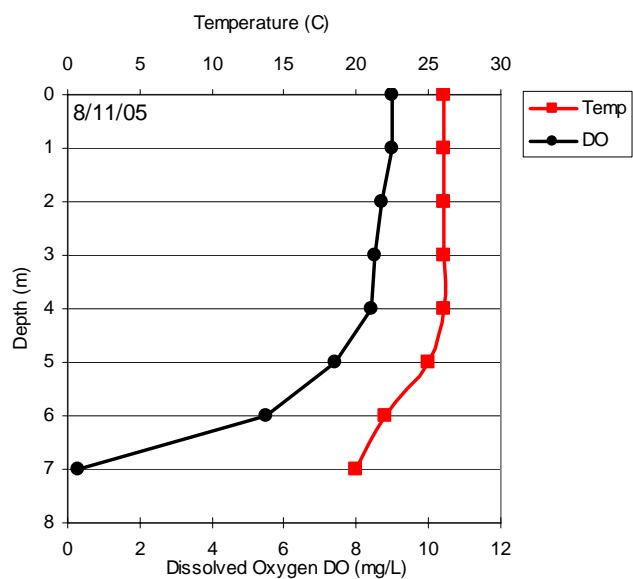
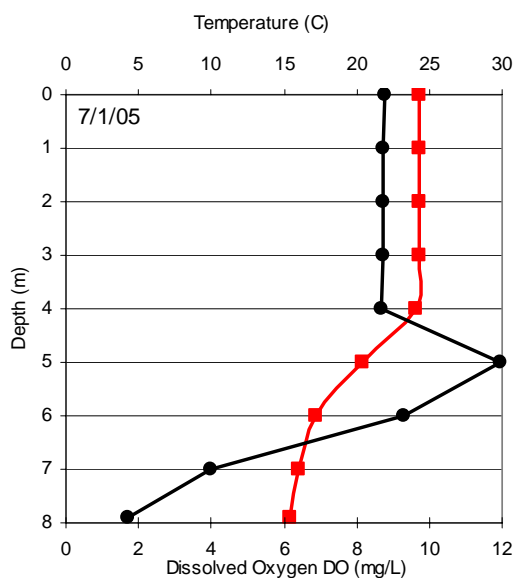
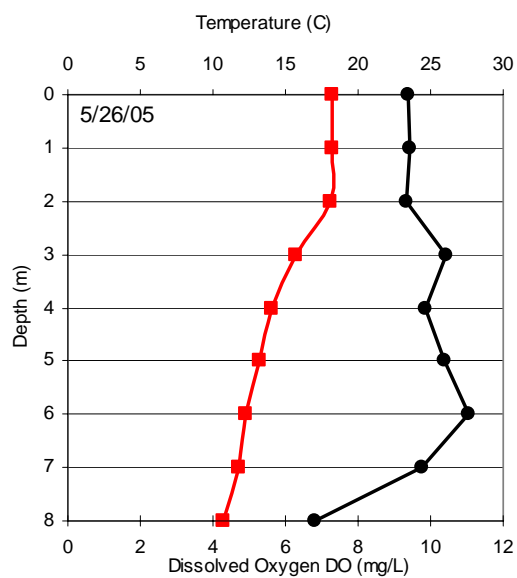
Temperature and dissolved oxygen profiles from Florence Lake, Sleeping Bear Dunes National Lakeshore, 2005.



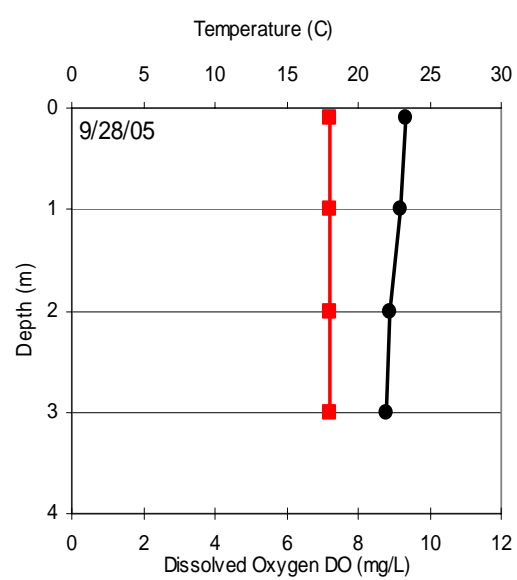
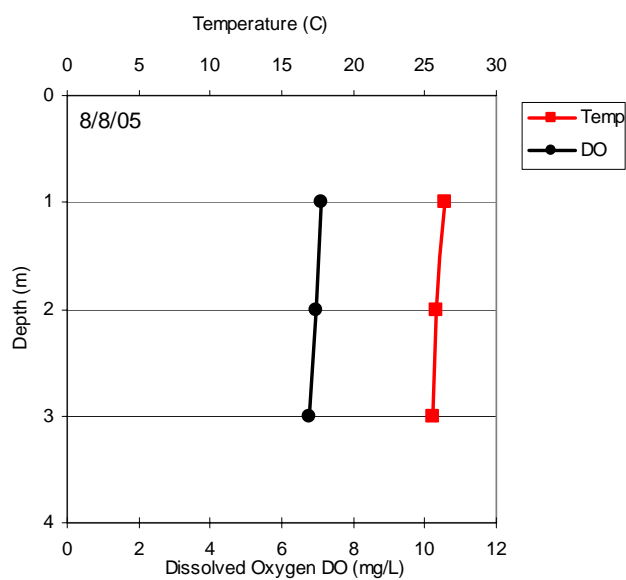
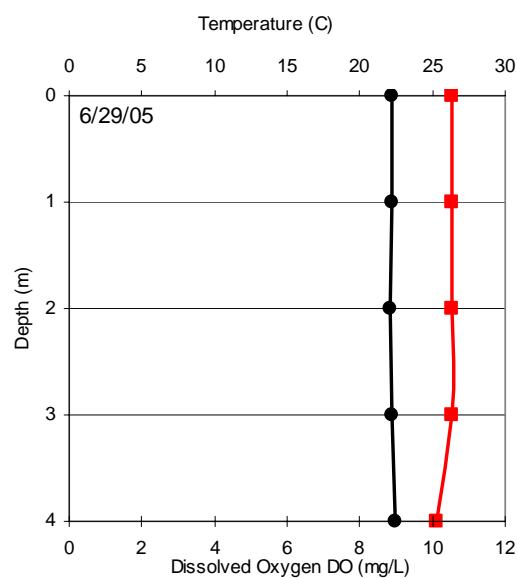
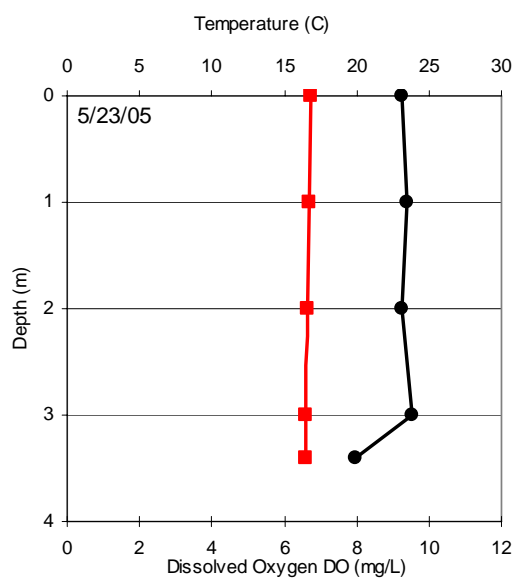
# Temperature and dissolved oxygen profiles from Lake Manitou, Sleeping Bear Dunes National Lakeshore, 2005.



Temperature and dissolved oxygen profiles from Round Lake, Sleeping Bear Dunes National Lakeshore, 2005.



Temperature and dissolved oxygen profiles from Shell Lake, Sleeping Bear Dunes National Lakeshore, 2005.



Temperature and dissolved oxygen profiles from Tucker Lake, Sleeping Bear Dunes National Lakeshore, 2005.

